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ADVANCED LOW COST G-CUING SYSTEM (ALCOGS)

By

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20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

The G-seat is a device that replicates in a flight simulator the pilot/seat interaction due to aircraft acceleration. The G-suit and seat shaker systems provide important cues to the pilot used in the control of the aircraft. These cues are believed to be particularly significant in high performance tactical aircraft. In order to investigate G-cuing philosophies and drive schemes, a system was developed with capabilities exceeding that of present G-cuing systems. which will allow the determination of how to obtain the maximum benefit from these cuing sources. The Advanced Low Cost G-Cuing System (ALCOGS) embodies the basic somatic capabilities of the first generation G-seat coupled with high response speed and system flexibility. ALCOGS combines G-seat, G-suit, and seat shaker systems into one integrated G-cuing system.

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SUMMARY

PROBLEM

The Advanced Low Cost G-Cuing System (ALCOGS) was developed to fulfill a need for a highly responsive and flexible research G-cuing system for tactical aircraft simulation. In order to answer questions pertaining to G-cuing system hardware and drive algorithms, a system was needed with capabilities exceeding that of existing G-seats.

Certain objectives were therefore established for ALCOGS, as follows: (1) bring G-seat, G-suit, and seat shaker together as one integrated system, (2) improve the response characteristics of primarily the G-seat, and secondly the G-suit, (3) accommodate both the conventional upright F-15 type attitude and the tilt back F-16 attitude, (4) attempt to design the system so as to lower the aggregate cost of the seat/suit/shaker system, and (5) investigate, develop, and embody in the final system the mechanical concepts which improve the somatic cuing quality of the G-seat.

APPROACH

ALCOGS is a hybrid system consisting of hydraulic and pneumatic drive elements. The system utilizes a flat plate/firmness bladder drive concept. The hydraulic actuators provide seat pan and backrest excursion and attitude changes, while the firmness bladders provide area of contact and localized pressure variations. The hydraulic actuator servos are electronically closed loop on position while the firmness bladder servos are electronically closed loop on pressure.

Three hydraulic actuators in the seat pan form a three post drive system, driving the seat pan top plane in three degrees of freedom; pitch, roll, and heave. A fourth hydraulic actuator provides longitudinal seat pan motion. Two more hydraulic actuators located in the seat pan provide a differential lap belt drive. Three hydraulic actuators in the backrest drive the backrest top plane in pitch, roll, and longitudinal degrees of freedom.

In addition, two hydraulic actuators drive radial wings located at the lower corners of the backrest.

A dual cell firmness bladder lays on the seat pan top plane, and a single cell firmness bladder lays on the backrest top plane. The pneumatic systems, firmness bladders and G-suit, employ a newly developed servo valve/booster manifold for increased flow and evacuation capabilities.

The seat shaker system operates over a 0 Hz to 40 Hz frequency range. The shaker drive consists of two variable frequency oscillators and a discrete input. The vibration exposure protection system is incorporated which deactivates the shaker system when the subject exceeds a permissible accumulated vibration level.

The ALCOGS software includes modules to drive the seat, suit, and shaker systems. The software gives the experimenter the capability to perform a wide range of alterations to the various drive schemes.

RESULTS

The G-seat drive actuators display a 30 millisecond rise time. The G-suit has increased pressurization and evacuation capabilities over previous systems. The seat shaker system provides 0.5 g capability from 4.5 Hz to 40 Hz.

ALCOGS was integrated with the Air Force Human Resources Laboratory Simulation Training and Research facility at Wright Patterson AFB, Ohio in December, 1977. The system was integrated with, and driven from, its software modules. The system is being used in an engineering and psychophysical test, evaluation, and development program, with the primary objective being the determination of the optimum, G-cuing hardware and drive algorithms for use in tactical aircraft simulation.

CONCLUSION

The Advanced Low Cost G-Cuing System has been demonstrated to be a highly responsive system. The system has proven to be easy to maintain and service and provides the flexibility needed for investigation into G-cuing drives and philosophies.

1.0 INTRODUCTION

In flight simulation, it is necessary to provide the pilot with kinesthetic information utilized in the control of the aircraft. Simulator motion systems provide such information by stimulating the vestibular sensory system, and to a lesser degree the somatic sensory system, presenting the pilot with a scaled version of the accelerations associated with the task being performed. Motion systems are limited, however, in their ability to provide sustained acceleration information due to excursion and velocity constraints. This becomes particularly apparent for high performance tactical aircraft, where only the leading edge of the simulated acceleration is provided to the pilot, followed by a subliminal washout. The G-seat overcomes this problem by directly addressing the somatic system, which consists of the muscle and flesh pressure receptors employed in perceiving physiological changes due to sustained acceleration.

The G-seat provides sustained acceleration cues by altering the elevation, attitude, and contour of the seat, thereby creating changes in localized body pressure, area of contact, and body position with respect to the seat. Thus a facsimile of the body/seat coupling due to inertial body movement induced by aircraft rotational and translational accelerations is reproduced without having to replicate the actual aircraft accelerations.

The Advanced Low Cost G-Cuing System (ALCOGS) was developed in response to questions that arose concerning the capabilities of the G-seat presently in use. The questions primarily concerned whether the mechanical capabilities of the G-seat were allowing the optimal usage of the seat as a cuing source. A system was therefore developed that includes the following: a second generation G-seat having increased response capabilities and improved cuing schemes, an advanced anti-G suit system, an improved seat shaker system, and the software to drive these systems. ALCOGS is integrated with the Wright Patterson AFB Air Force Human Resources Laboratory Simulation Training and Advanced Research System (STARS).

2.0 BACKGROUND

The Link Division of the Singer Company developed the first G-seat for the Advanced Simulator for Pilot Training (ASPT) in 1971 (Reference 1). This device, now commonly referred to as the first generation G-Seat, has since become an integral part of a number of other tactical flight simulators. The seat provides sustained acceleration cues beyond the capabilities of motion systems.

The first generation G-Seat (Fig. 1) consists of four basic elements; a seat pan cushion, a backrest cushion, thigh panels, and an active lap belt. All the elements are pneumatically driven. Not included as part of the G-seat are anti-G suit and shaker systems.

The seat pan cushion consists of a mosaic of sixteen pneumatic metal bellows arranged in a four by four array. The backrest cushion consists of a mosaic of nine bellows arranged in a three by three array. The seat pan is driven in three degrees of freedom; pitch, roll, and heave. The backrest is also driven in three degrees of freedom; pitch, roll and surge. Both cushion assemblies provide sustained acceleration cuing through the primary G-seat drive concepts of varying cushion surface elevation, surface attitudinal orientation, and surface shape, all of which can be executed simultaneously. The mosaic approach is very useful in altering the cushion surface shape. The surface shape, or contour, variations provide localized pressure change sensations on the pilot's body, corresponding to being pushed into the seat during high acceleration.

The thigh panels are located longitudinally along and on top of the outboard edges of the seat pan cushion. Three independently driven radial bellows make up each panel. These panels vary the area of flesh to seat contact in the thigh region as a consequence of simulated aircraft lateral, longitudinal, vertical, and roll acceleration.

The lap belt is driven by a pneumatic actuator housed under the seat. The belt drives in extension and contraction about some "buckle-up" state.

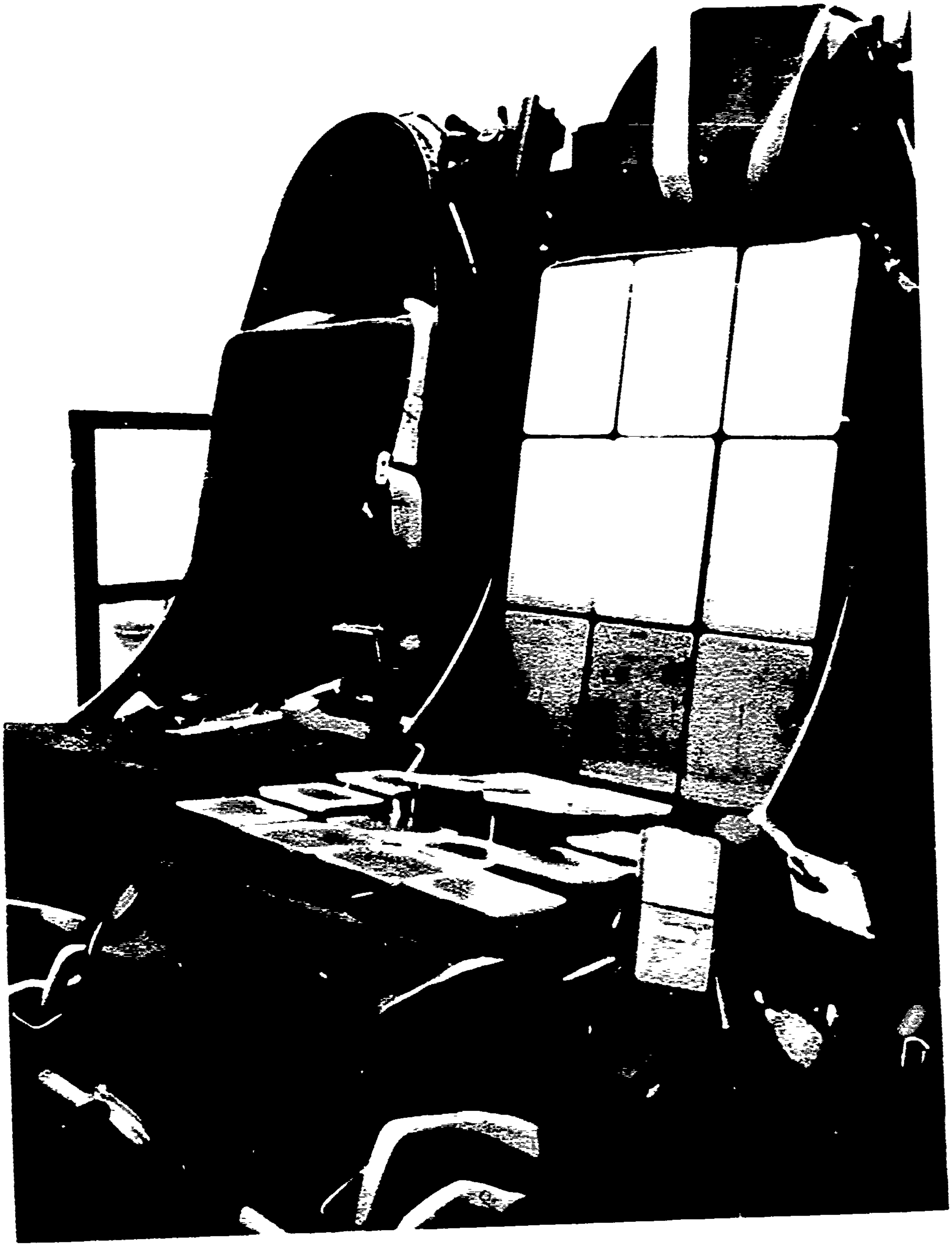


Figure 1. First Generation G-Seat

The pneumatic control for the first generation G-seat is positionally an open loop system. A software program calculates an excursion for each mosaic element based on simulated aircraft acceleration. This excursion is transformed into a pressure command for each cell, utilizing a predetermined knowledge of each bellow's spring rate and an estimate of subject load on each mosaic element. This command is converted to a voltage by the I/O linkage, which drives an electro-pneumatic transducer. The transducer varies pressure in each cell in direct proportion to the applied voltage.

The open loop nature of the first generation G-seat was one of several reasons for the development of ALCOGS, (Fig. 2). The above mentioned open loop pneumatic system has a frequency band pass of approximately 1.0 Hz (i.e. -3 db at 1.0Hz) (Fig. 3). The low pass nature of this system coupled with low host simulator iteration rates tends to restrict this device to that of a sustained cuing device and contributes to time delay (Reference 2). ALCOGS was designed to be a more responsive, flexible G-seat. By having a system with a frequency bandpass on the order of 10 Hz, or a 30 msec rise time, research could begin towards establishing what hardware response levels are optimal for G-seat simulation fidelity. The high response would also allow an investigation into using the G-seat for transient or onset acceleration cuing, in addition to the sustained acceleration cuing provided by the seat. To improve the response to such a degree, a positionally closed loop control system would have to be used on each of the seat actuators. A closed loop system would also reduce the position error inherent in the open loop control system of the first generation G-seat.

Prior to ALCOGS, the G-seat, anti-G suit, and seat shaker were all separate systems. ALCOGS would bring the three together into one overall stand alone G-cuing system. Other features of ALCOGS would consist of improvement of the lap belt system by using two actuators closed loop on position, one on each end of the lap belt, allowing a differential drive. Visual

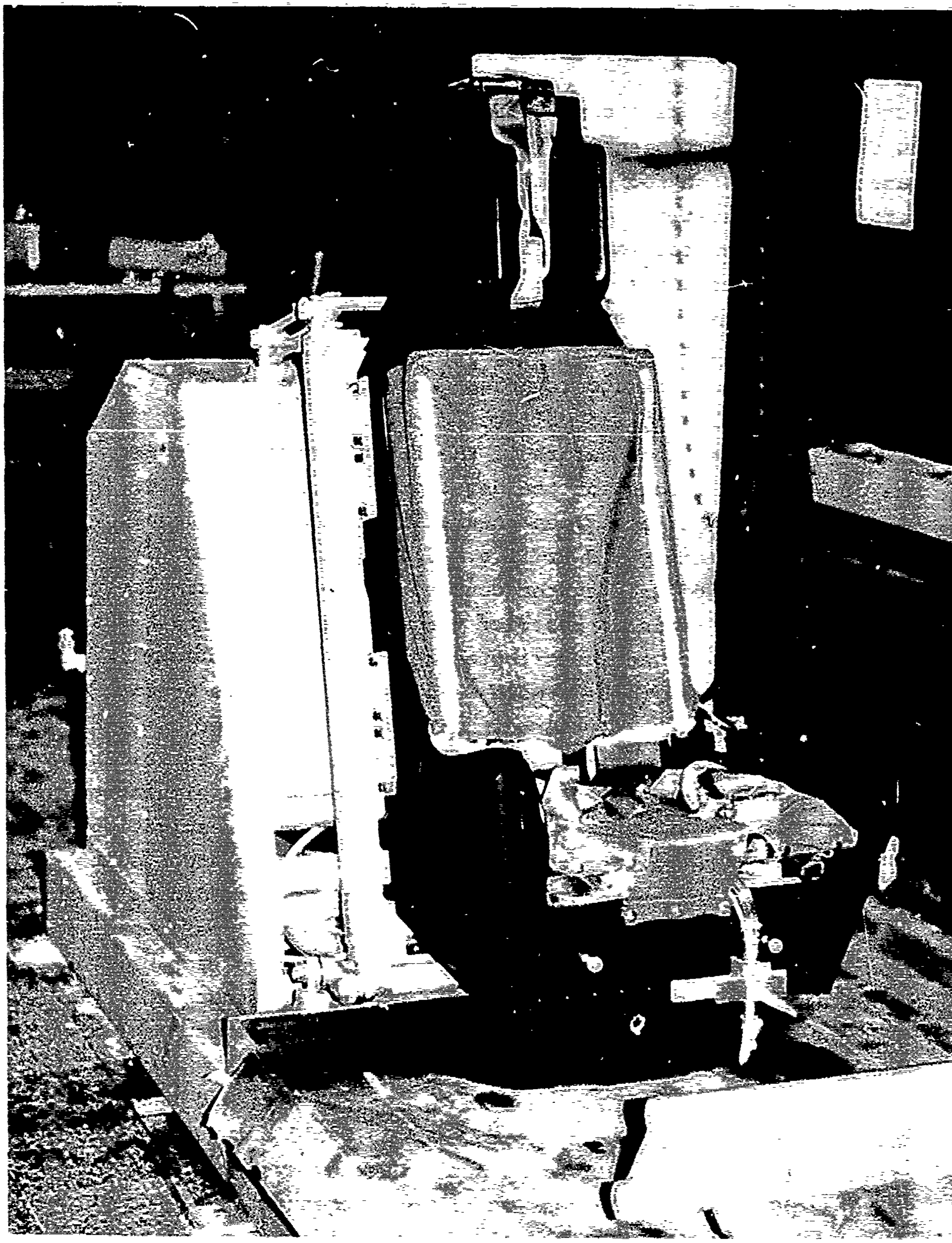


Figure 2. Advanced Low Cost G-Cuing System

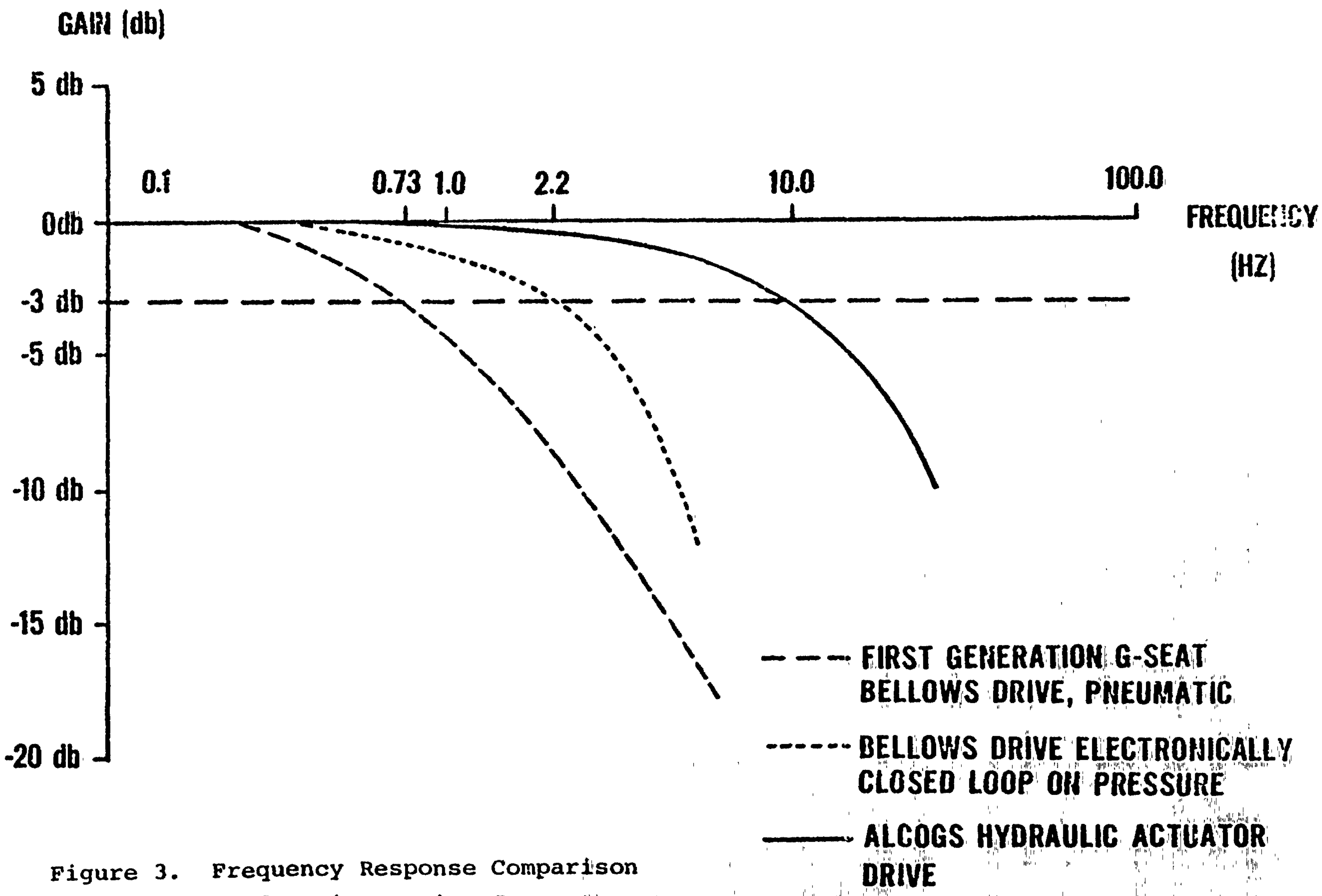


Figure 3. Frequency Response Comparison Of Various Drive Concepts

fidelity of the seat as compared to the actual aircraft seat would be improved by the elimination of the thigh panels, utilizing other means to provide the cues attributed to the thigh panels.

As a research tool, flexibility is important. Therefore ALCOGS would have the capability to be used in the conventional attitude of an A-10 or F-15 type seat and also in the 30° tilted back angle of the F-16 seat.

One other objective of ALCOGS was to reduce the system procurement cost. It was assumed from the outset that closing the loop on the servo drives would result in an increased cost per servo. However, the number of actuators in ALCOGS would be considerably less than in the first generation seat, which employs up to thirty-two servo drives. Another means to reduce cost would be to reduce hardware package size. The design would be directed towards standard modules such that the primary assemblies, seat pan, backrest, and lap belt mechanisms, could be retrofitted into various aircraft seat frames with a minimum amount of modification.

3.0 ALCOGS HARDWARE

3.1 Initial Configuration

The initial configuration of ALCOGS (June 1976) consisted of a G-seat system which was made up of a seat pan assembly and a backrest assembly, a shaker system, and an anti-G suit system. In addition an electronics control cabinet (ECC) would be stationed near the G-cuing system, and would contain all the electronics, control switches, and inputs necessary to operate the system.

The seat pan cushion would be driven in four degrees of freedom, longitudinal (X-axis), heave (Z-axis), pitch and roll. The cushion assembly was made up of the following elements:

1. Three hydraulic actuators with position feedback devices to drive pitch, roll, and heave degrees of freedom.
2. Longitudinal travel hydraulic actuator with position feedback device.
3. Dual cell pneumatic firmness bladder, with pressure feedback.
4. Upper plane with passive raised surface ramps to provide increased area of contact cuing about the thighs.
5. Passive blocks on the upper plane to provide increased pressure cues to the ischial tuberosities in the buttock region.
6. Lap belt system consisting of two hydraulic actuators and position feedback devices.

The backrest cushion would be driven in three degrees of freedom, longitudinal, pitch, and roll. The backrest elements were as follows:

1. Three pneumatic metal bellows with position feedback devices to drive pitch, roll, and longitudinal degrees of freedom.
2. Two pneumatic radial drive bellows with position feedback devices to provide increased area of contact cuing in the lower back region.
3. Single cell firmness bladder with pressure feedback.

The hydraulic approach in the seat pan was selected for two reasons. It displayed potential for sub-assembly compactness, a design goal for cost reduction, and it provided the means for investigating the possible elimination of the separate shaker system hardware. The shaker vibrations could potentially be input via the seat actuators. The use of pneumatic metal bellows in the backrest was predicated primarily on the need for cushion thinness. The bellows provide a thinner package than do hydraulic actuators.

The anti-G suit would be a system patterned after prior Link-built systems where suit pressure is a function of simulated aircraft acceleration. The ALCOGS suit would have increased evacuation capability. A pilot's press-to-test function would be added as part of the system drive.

The shaker system would consist of a short body hydraulic actuator mounted at the base of the seat frame/cockpit mounting structure. The system would operate closed loop on actuator position.

3.2 Final Configuration

3.2.1 G-Seat

As a result of the development and component test phase, a significant change was made to the basic configuration previously described. Hydraulic actuators replaced the three backrest pneumatic bellows and the two radial pneumatic bellows on a one-for-one basis. The reasons for this change are described later.

The seat pan consists of a total of six hydraulic actuators. Three actuators form a three-post support system and drive the seat pan upper plane in pitch, roll, and heave. Each of these actuators has an excursion range of ± 1.25 inches. The two lap belt actuators are located in the seat pan and drive the lap belt in the X and Z axis and differentially in the Y axis.

Both lap belt actuators have a stroke of ±1.5 inches. The seat pan upper plane consists of an undercarriage and top plate. The longitudinal actuator is mounted on the undercarriage and drives the top plate fore and aft ±1.0 inch. This motion is cascaded on seat pan pitch, roll and heave capability. Mounted on the top plate are the passive tuberosity blocks and thigh ramps, and on top of them is the dual cell firmness bladder.

The aforementioned is mounted within the volume of the seat pan box which is approximately 15" X 15" X 6" in dimension. (Figs. 4,5). This is in turn mounted in the seat frame occupying the volume normally occupied by the survival kit in the actual aircraft. The seat pan assembly can be removed as a unit from the seat frame for maintenance.

It is not necessary to remove the entire assembly to work on a particular actuator. The actuator sub-assemblies are modular. There are four such modular sub-assemblies in the seat pan; the front actuator, two combination side/lap belt actuator sub-assemblies, and the undercarriage containing the longitudinal actuator. By removing the undercarriage, the other three sub-assemblies are exposed. The sub-assembly to be serviced is then either replaced or placed on a universal test manifold for service. Because of this modularity and ease of removal, no other part of the system need be disturbed.

The backrest assembly contains five hydraulic actuators packaged in a volume 15" X 21" X 3 3/4" in dimension (Fig. 6). Three actuators drive the top plate in the same manner as in the seat pan. The other two actuators drive the radial wings located in the lower corners of the top plate. Mounted on the top plate is a single cell firmness bladder.

As in the seat pan, the backrest actuator sub-assemblies are modular. Any one of the three top plate drive actuators can be removed separately. Two radial actuators and wings are combined into one subassembly and is easily removed as such. The backrest assembly itself can be removed as a unit from the seat frame.

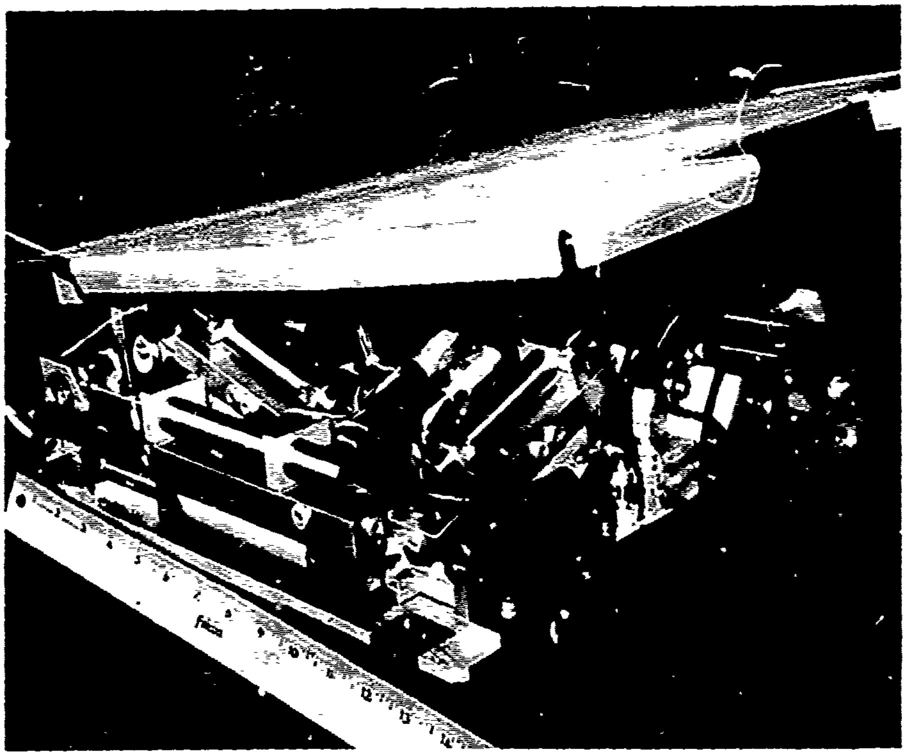


Figure 4. Seat Pan Assembly

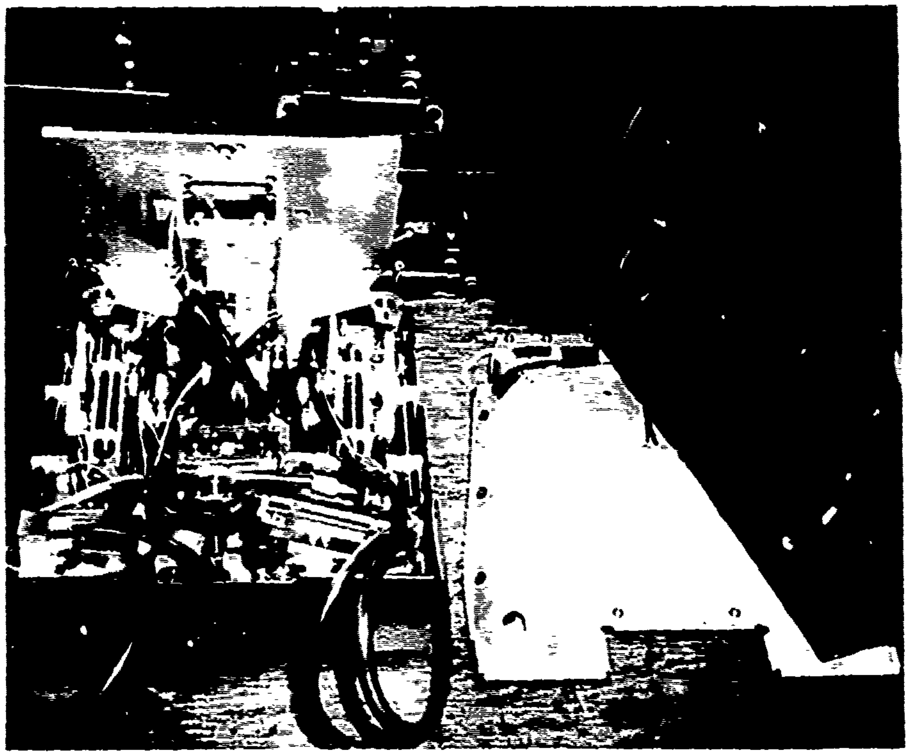


Figure 5. Seat Pan - Top Plane Removed, Bladder Folded Back

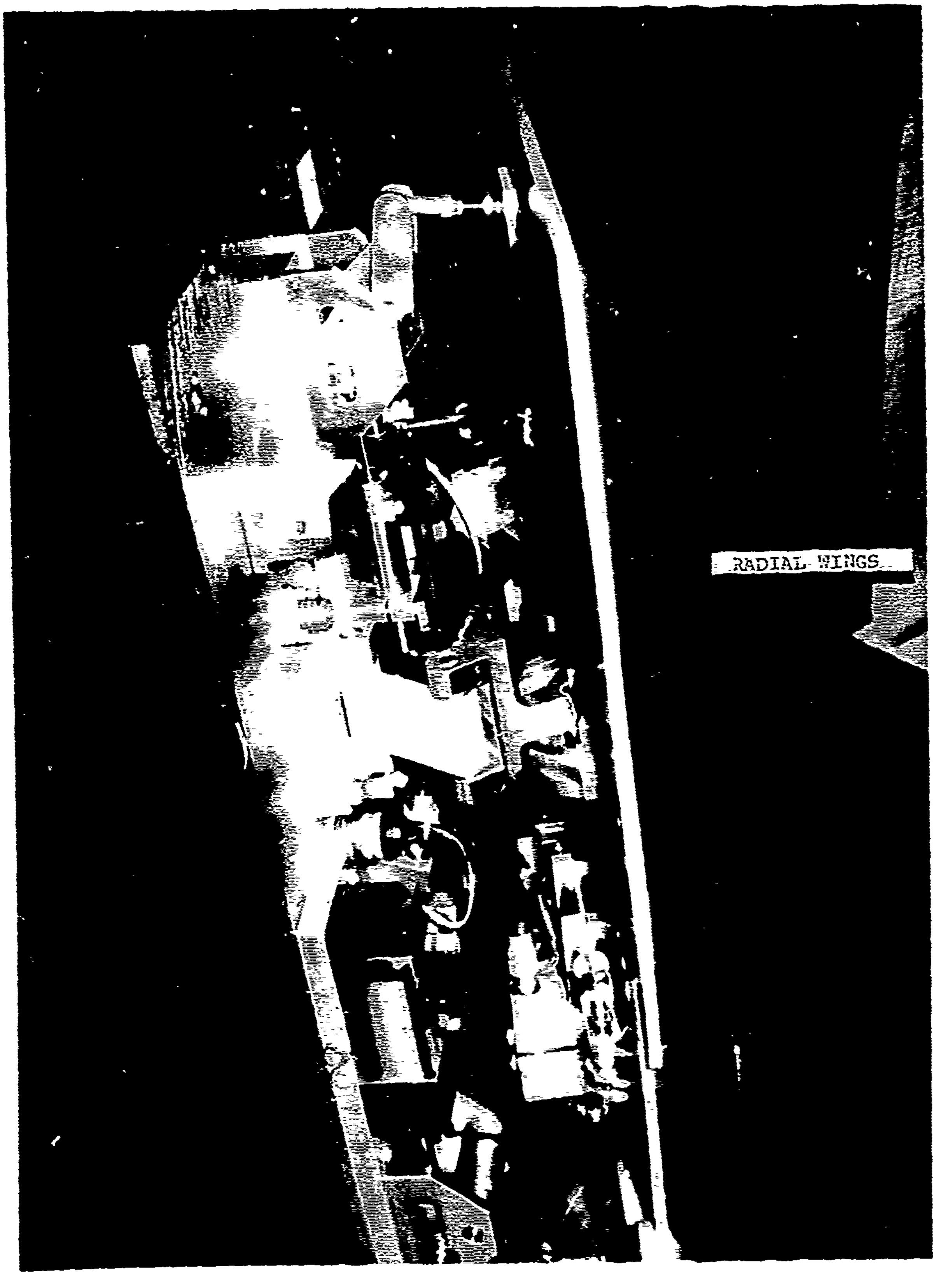


Figure 6. Backrest Assembly - Side View

The shaker actuator is vertically mounted behind the seat frame on the aft equipment bay frame. By means of a bell-crank mechnism, the shaker drives a weldment upon which is mounted the seat frame. It is this weldment and its associated linkages that permit the seat to vary between the F-15 and F-16 seat configurations.

Pneumatic supply and vacuum, and hydraulic supply and return are available to the seat through the aft equipment bay. The pneumatic servo valve/booster assemblies for control of the firmness bladders and anti-G suit are located here. Also located in the aft frame are an electrical junction box and hydraulic distribution manifold. The junction box provides an interface between the ECC and the aft frame and seat assemblies. The hydraulic distribution manifold distributes fluid to the seat pan cushion, backrest cushion, and shaker actuator and controls fluid flow during standard and emergency shutdown. This distribution is controlled by solenoid valves driven from the ECC. Fig 7 shows the schematic organization of the G-cuing system.

3.2.1.1 ALCOGS G-Seat

Early in the development phase an effort to validate some of the drive concepts being employed in ALCOGS was made using the ASPT simulator facility. ASPT has a first generation G-seat in a T-37 cockpit, which was modified by laying a flat plate on top of both seat pan and backrest surfaces. On the seat pan plate was mounted passive thigh ramps and ischial tuberosity blocks. The pneumatic thigh cells were removed from the seat. The firmness bladders were secured on top of the flat plates. This experiment and conclusions reached have been documented (Reference 3). A summary of the study follows.

Experiments were run to examine several areas.

1. Validity of G-estimation through bladder pressure variations: The subjects, seated on the firmness bladders, estimated G loading as a function of bladder pressure. The subjects were able to discern changes in magnitude and direction.

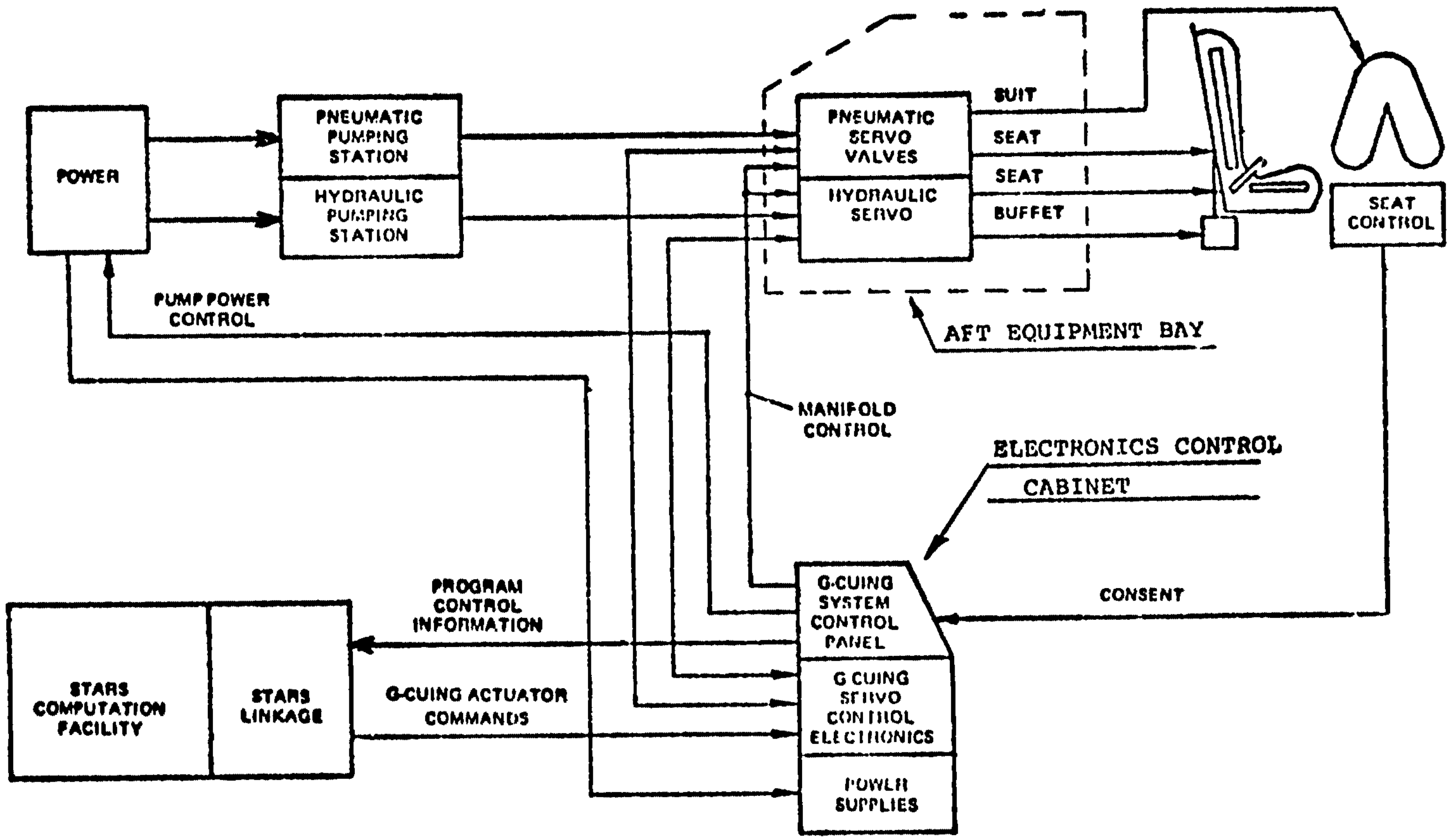


Figure 7. Schematic Organization of G-Cuing System Components

2. Flatplate/firmness bladder integrated drive: The seat pan and backrest planar drives were activated and the subjects were again asked to estimate G's. Results are shown in Fig. 8 for positive X-axis accelerations (thrusting) in which both the bladder and top plate are driven. Fig. 9 shows subject estimates for both positive and negative X-axis accelerations. For negative X, the bladder pressure remains constant, and the cue is perceived only through planar motion.

3. Backrest drive reversal: A question arose as to the validity of the backrest drive philosophy in which for positive X, the backrest tips bottom forward, top aft and vice versa for negative X. The question addressed whether or not a reversal of the drive would give a better cue; (e.g., tipping the backrest top forward, bottom aft for positive X, and vice versa for negative X). The drive was thusly altered and the simulated acceleration changes were made from a midpoint of X=0.125. Interestingly, the perceived accelerations were of the right magnitude, but all in the wrong direction, as shown in Fig. 10.

The above mentioned experiments indicate that bladder pressure changes can be used to provide acceleration cues. Planar movement was also found to provide significant cuing. The two drives, bladder and planar, work together to provide a broad range of simulated acceleration cues to the pilot.

3.2.1.2 Pneumatic Servo System

The original intent with respect to the backrest cushion was to use pneumatically driven metal bellows as the drive mechanism. The servo used in the first generation G-seat, a control valve mechanically closed loop on pressure, and booster relay combination, could not meet the response specifications for ALCOGS and does not provide loop closure on position. (The Advanced Systems Division of the Air Force Human Resources Laboratory, Wright-Patterson AFB, OH., investigated an improved G-seat pneumatic system soon after the first generation G-seat was operational in the ASPT). This pneumatic system was closed loop on position (Reference 4). To develop a closed loop servo that would

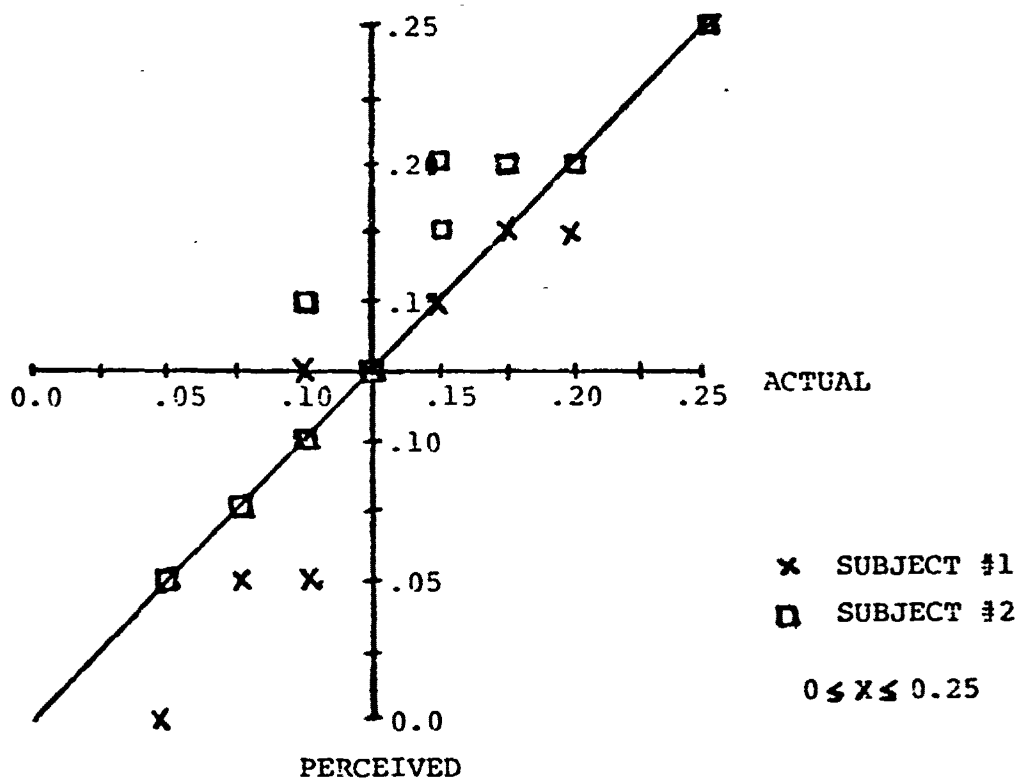


Figure 8. Perception of X-axis acceleration using active backrest and firmness bladder.

SIMULATED ACCELERATION	PERCEIVED ACCELERATION
$\ddot{X}$ = +0.1	$\ddot{X}$ = +0.1
-0.2	-0.1
-0.05	0.0
+0.175	+0.25
-0.1	-0.1
-0.15	-0.15
+0.075	+0.075
-0.25	-0.2
+0.05	+0.075
-0.125	-0.1
-0.3	-0.25
-0.075	-0.05
+0.5	+0.375

Figure 9. Perception of positive and negative X-axis acceleration using active backrest and bladder.

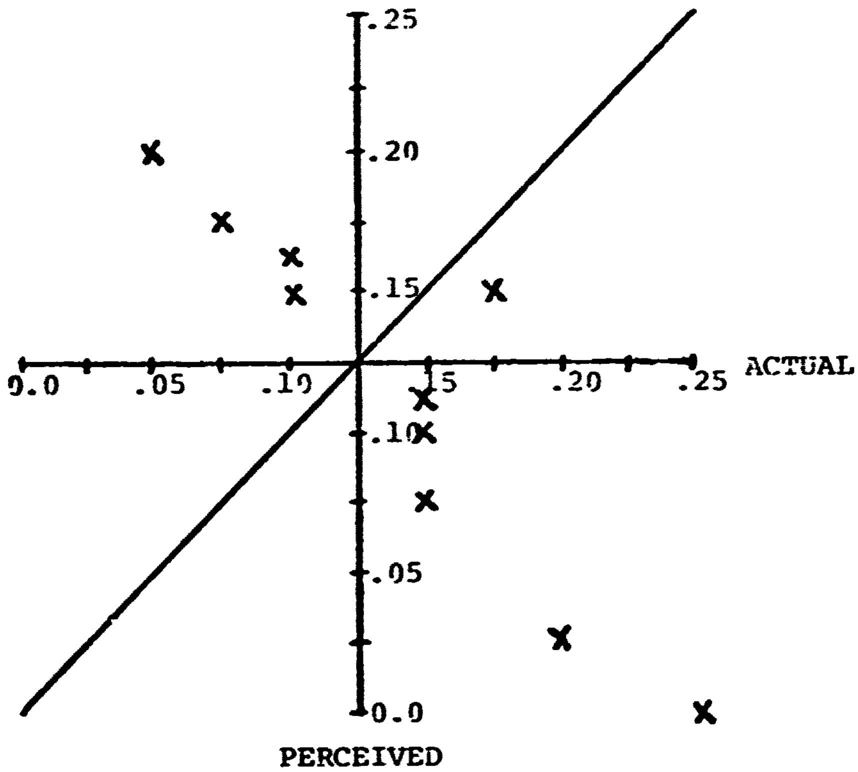


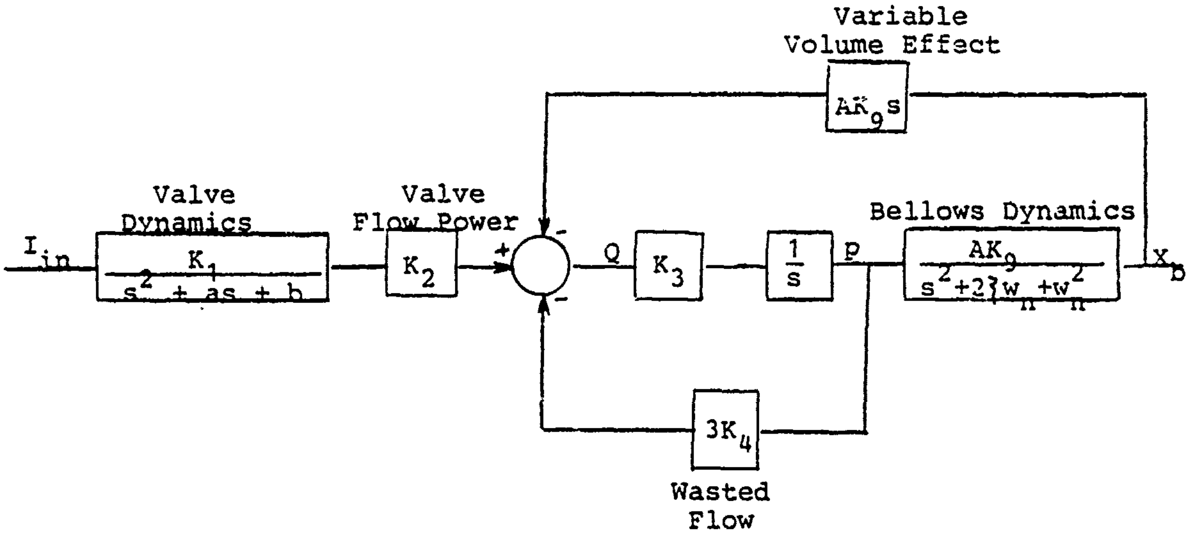
Figure 10. Perception of X-axis acceleration with altered drive.

meet the 30-millisecond rise time specification, it was necessary to model the valve/bellows system. Models were generated utilizing two different valves; one was the pressure control valve from the first generation seat, and the other was a flow control valve. Experiments with the two valves deadheaded show the flow control valve has better response characteristics than the pressure control valve. A block diagram of the flow valve/bellows model is depicted in Fig. 11.

Several computer programs aided in the model development. A flow analysis routine determined some of the necessary constants pertaining to valve flow rates and actuator flow requirements. Another routine calculated the effect on the overall system transfer functions of variations in system parameters. A root locus program and Bode analysis program gave theoretical frequency response information.

The root locus and Bode analysis showed that simply closing the servo loop on position would not yield the desired response characteristics. To achieve the necessary system bandpass, the gain would have to be increased to a point where the system either went unstable or would have undesirable damping characteristics. A cascaded compensator network was designed to improve the system stability. This did not solve the response problem, however. Re-evaluation of the model showed that the system was sensitive to changes in the paramaters of load and volume, which vary during dynamic operation. The compensator network was designed for specific values of load and volume. An optimal compensator for all values of load and volume could not be determined due to the large variations of open loop pole location due to these parameters.

Another problem with the bellows system involved the feedback device. As stated before, a design goal was to maintain all components within the volume occupied by the survival kit and parachute pack. A feedback device was not found that could meet this requirement. Devices mounted internal to the bellows were



K_1, K_2, K_3, K_4, K_9 - Gain Constants

A - Bellows Effective Area

w_n - Bellows Natural Frequency

ζ- Bellows Damping Ratio

I_{in} - Input Current

X_b - Bellows Position

Q - Flow Rate

p - Pressure

Figure 11. Flow Valve/Bellows Open Loop Block Diagram

investigated but did not have a high enough frequency response.

These problems were not without solution, but due to the limited time frame allowed for the development of ALCOGS a major change was necessitated. This change was the substitution of three hydraulic actuators for the three backrest bellows and acceptance of a slightly thicker backrest assembly. The same type stability problems existed in the radial element bellows and these too were replaced by small hydraulic actuators.

Pneumatics remain a part of the G-cuing system in the form of the firmness bladders and G-suit. The aforementioned problems do not arise in the bladder servo loop. The bladder can be modeled as a first order system, just the volume the valve drives into, not the second order system represented by the bellows. Since flesh pressure and area of contact variations form the functional effects of the firmness bladders, position is of secondary concern, and pressure feedback is used to close the loop. The pressure transducers are mounted in the cushion assemblies and plumbed to the bladders. Due to the volume of the bladders, approximately 24 in^3 for each half of the seat pan bladder and 100 in^3 for the backrest bladder, the peak air consumption demands are higher than the flow valve can provide by itself. Larger capacity valves were tested; however these valves had a detrimental effect on system frequency response. Therefore, booster valves to increase the flow rate were manifolded together and driven in unison with the smaller capacity flow valve providing the pilot signal. A two booster manifold is used for each side of the seat pan bladder and a four booster manifold is used for the backrest bladder. This configuration allows the necessary flow rates that must occur to achieve the specified response.

The pneumatic servo drive is illustrated in Fig. 12. The servo receives a commanded pressure signal from the computer. The signal is summed with the pressure feedback and bias signal. The bias signal provides the bladder pressure corresponding to the 1 G neutral state. The system is referred to as a Type 0 control system, in which a constant error signal is necessary to maintain a constant bladder pressure. The magnitude of the error signal is a function of gain. Also, the total range of the bias and commanded pressure signals are a function of gain. To correct for this, trim pots are located on the bias and commanded pressure signal paths. So, as gain is varied, the experimenter must readjust the signal range.

The bladders exceeded 100,000 cycles of full stroke (0-2 psi) operation without failure. Drift tests resulted in 2.7% of full scale drift over twelve hours.

The bladders were set up such that rise time was 30 msec. Bode plots and time response data for the firmness bladders can be found in Appendices A and B.

3.2.1.3 Hydraulic System

During the development phase, a seat pan hydraulic actuator test sample was manufactured and fitted to a test stand permitting the actuator to be loaded with up to 80 pounds of dead weight. The actuator assembly fulfilled all expectations in its performance. It met the response specification requiring the actuator to be able to cycle at 1Hz full stroke. That is, the system should be able to pass a 1Hz sinusoid with no flow or velocity limiting.

A test sample of the lap belt actuator also performed to specification. The lap belt test actuator was also used in tests of the shear pin coupling device. The pins were designed to shear at 100 pounds. In the tests, all sample pins sheared at forces between 94 pounds and 107 pounds.

Two different hydraulic actuator assembly designs emerged to replace the backrest pneumatic bellows. One was a version of the bellcrank assembly used in the seat pan, and the other was a slide link mechanism. Tests run on both assemblies showed equivalent response characteristics. It was decided to employ the slide link assembly on the basis of packaging. Due to the thinness of the backrest package and the modular design objective, the low profile slide link was a more attractive assembly. The bellcrank configuration would require the servo valve to be mounted separate from the cylinder and follow-up device, adversely affecting serviceability. In contrast, the slide link incorporates all three items in one assembly.

The servo loop for the hydraulic actuator is depicted in Fig. 13. The hydraulic servo is a Type 1 system. The error signal used to drive the servo valve goes to zero in the steady state. A variable bandpass filter smooths the discontinuities in the computer signal due to the computer iteration rate. An erect signal ramps the actuator to midstroke, the neutral position, when the seat is powered up. Upper plane excursion is referenced to the neutral position.

Time response and frequency response data for all the system hydraulic actuators can be found in Appendices A and B. Life tests on the seat pan hydraulic actuator resulted in 100,000 cycles of full stroke operation with no failures or leaks developing in the assembly. Drift tests resulted in 0.22% of full stroke drift over a twelve hour period.

3.2.2 Anti-G Suit

In an actual aircraft, the anti-G suit system is a low pressure pneumatic system whose prime function is to regulate the pressure of the pilot's anti-G suit as a function of increasing G forces. By this means, the suit provides pilot protection against greyout and blackout and provides the pilot with a very good indication of the acceleration to which the aircraft is being subjected. The accurate simulation of the anti-G suit operation not only enhances the realism of the training environment, but provides significant sustained acceleration cues to the pilot used in control of the aircraft.

In G-suit implementations prior to ALCOGS, a pressure control valve and booster relay were used to regulate suit inflation. The deflation rate for this system was slower than desired, so one of the areas investigated in developing ALCOGS was the use of the two stage booster manifold to improve the response of the G-suit, particularly in deflation. Vacuum exhaust of -5 psi applied

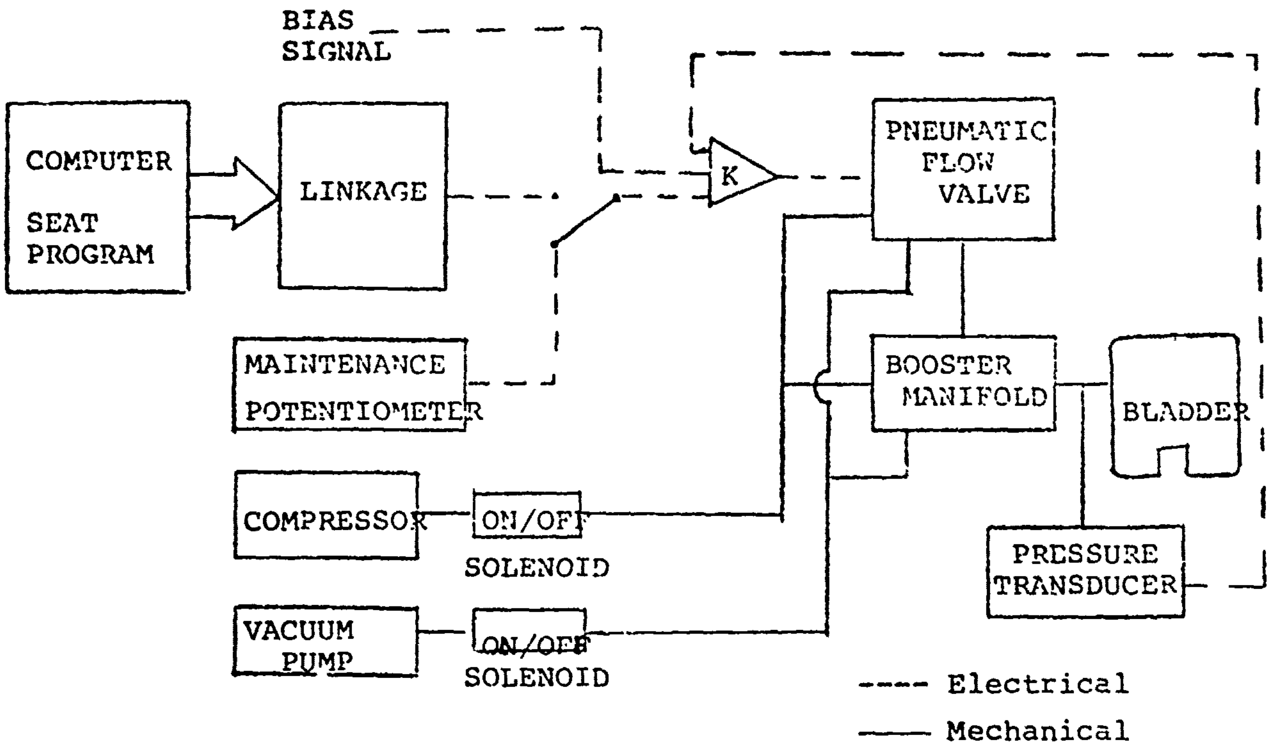


Figure 12. Firmness Bladder Control System

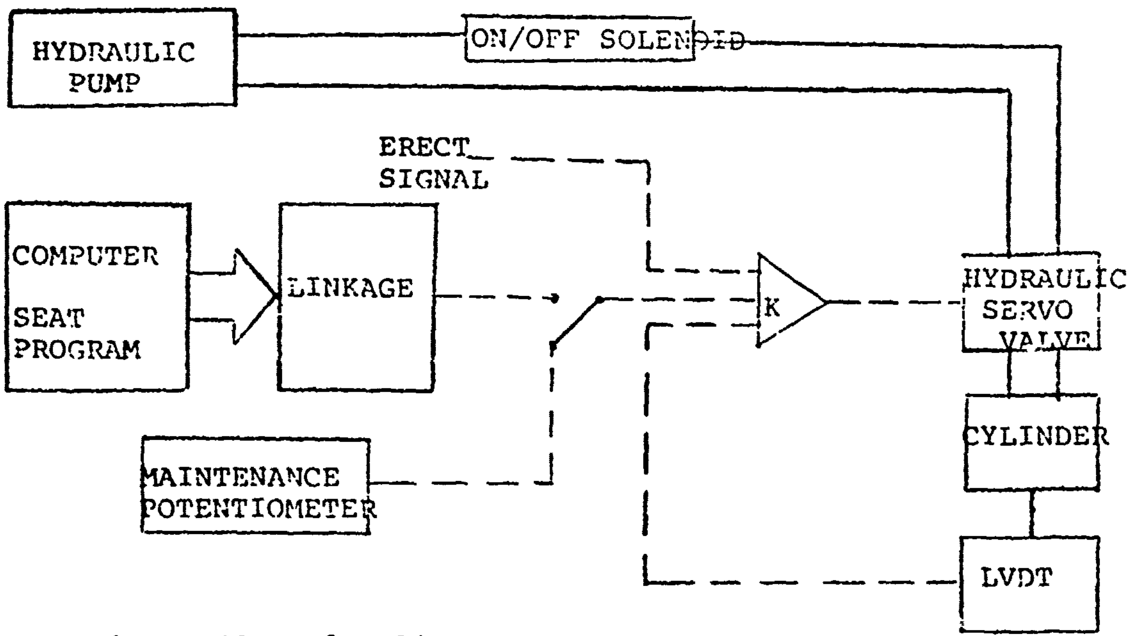


Figure 13. Hydraulic Actuator Control System

to the manifold aids in depressurization of the suit. Fig. 14 displays step response data for 0-5 psi steps in pressurization and exhaust for various drive mechanisms. As can be seen, the best response is obtained with the two stage manifold with vacuum exhaust.

The G-suit control system is shown in Fig. 15. When the system is powered up from the ECC, two solenoids open supplying compressed air and vacuum to the system. Under software control, the commanded pressure signal is issued from the computer through the linkage and drives the pressure control valve, which in turn controls the inflation or deflation of the suit. Unlike the G-seat pneumatic bladders where very high response is sought, the G-suit can afford the utilization of the lower responding pressure control valve wherein loop closure is mechanically implemented on pressure.

The ALCOGS G-suit also incorporates a pilot initiated press-to-test button. As the button is depressed, a pressure proportional to the button position is applied to the suit. The commanded pressure signal from the press-to-test button is combined with the commanded pressure signal from the linkage or maintenance potentiometer to permit functional press-to-test capability at all times. This G-suit mechanization will be used in several other simulator programs, including 16 G-cuing systems going into the Air Force's F-4E simulators and the ASPT.

3.2.3 Seat Shaker

The shaker system provides vibration and buffet cues at the pilot's seat. It provides both continuous vibratory cues and discrete cues. The continuous cues are stall buffet, background rumble, speedbrake buffet, runway rumble and landing gear buffet. The discrete cues are touchdown bumps, landing gear up/down bumps, runway joint bumps, and a discrete aero buffet.

The hydraulic actuator previously used in shaker systems was quite large and was mounted longitudinally aft of the seat frame as a consequence of its size. This orientation adversely

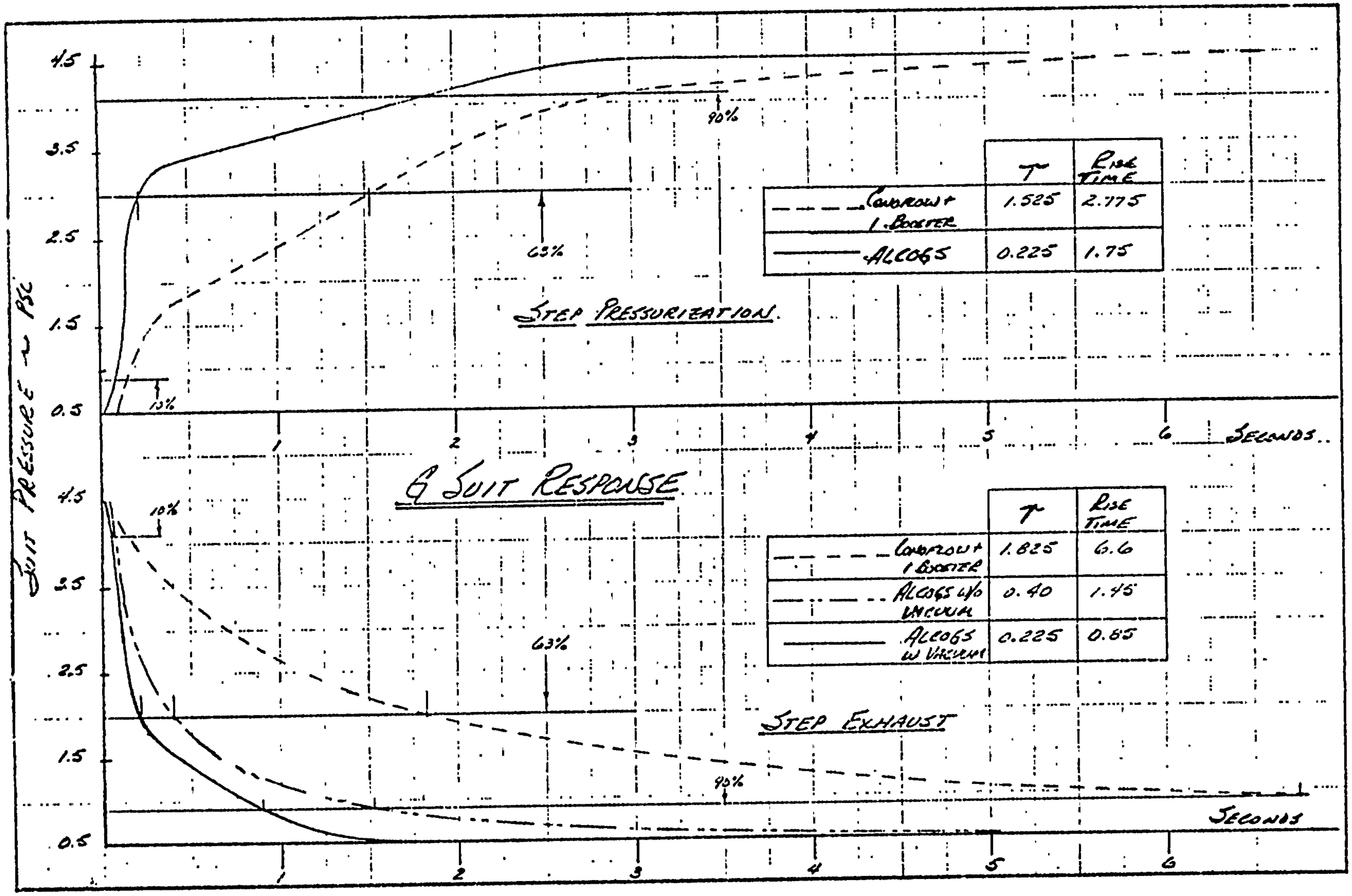


Figure 14. Anti-G Suit Step Response Data

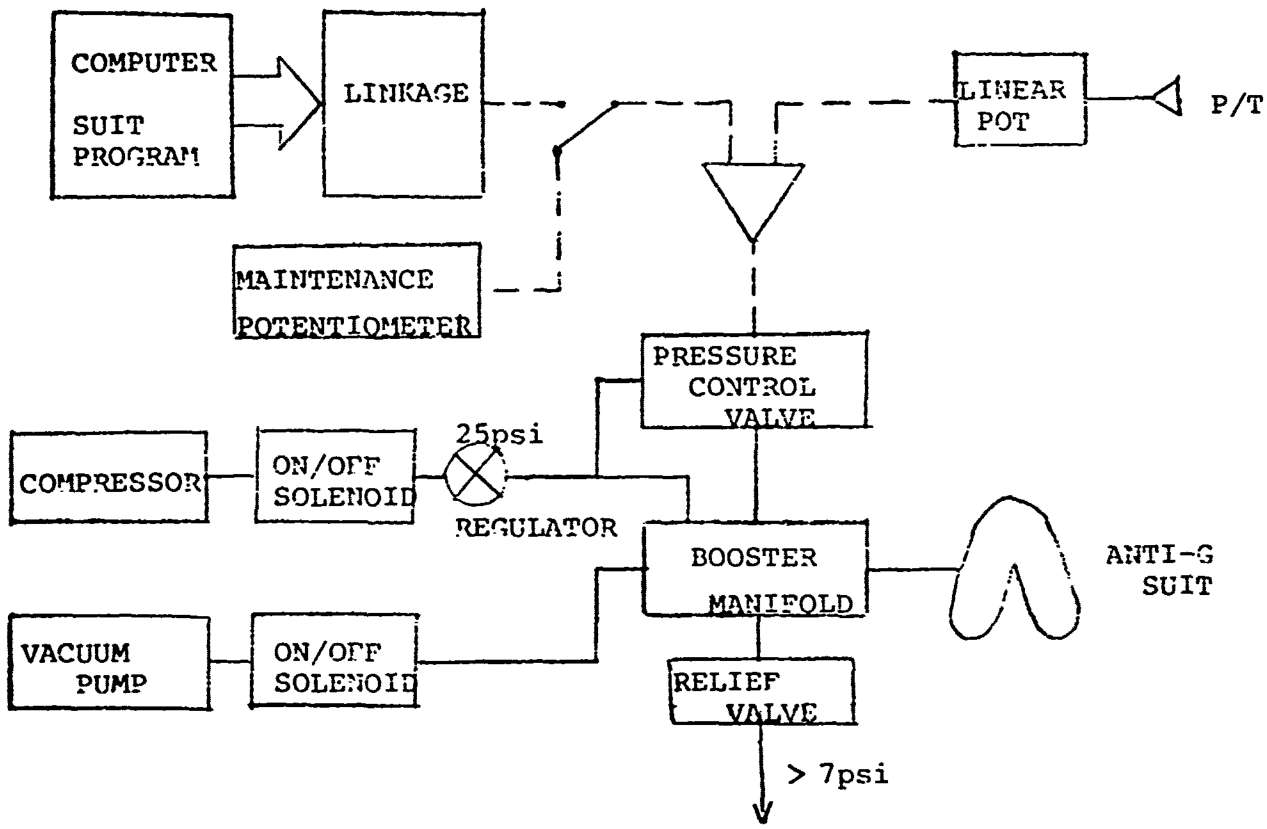


Figure 15. Anti- G Suit Control System

affects the packaging of the system, and increases cost, especially in a retrofit situation. A more compact actuator was selected for use on ALCOGS and is mounted vertically behind the seat.

The shaker system provides vibratory cues between frequencies of 0 Hz and 40 Hz at amplitudes up to ±0.25 inches. The system can provide accelerations of 0.5g throughout the 4.5-40 Hz frequency spectrum. The shaker actuator is driven by the summation of two variable frequency oscillators (VFO's) and a discrete channel input (Fig. 16). Each VFO constructs a sinusoidal signal from two inputs, a voltage proportional to the desired signal frequency and a voltage proportional to the amplitude of the signal. The shaker actuator servo loop is identical to that illustrated in Fig. 11 and is closed loop on position through an LVDT follow-up device.

To protect against mechanical resonances in the seat assembly, the output of each VFO is limited to provide a maximum of 0.5 g. The limiter circuit limits the amplitude signal according to the following equation:

$$A = \mathrm{MIN}\left[Aj\ \frac{k_1 f^2}{0.5} + (k_2 f)_{f>16.5}\right]$$

where

A = amplitude of signal

f = frequency of signal

k_1, k_2 = limiter gain constants

k_1 attenuates the permissible amplitude to alleviate problems in the region of mechanical resonance, which is 14 Hz to 17 Hz. The second term, $k_2 f$, increases the permissible amplitude for frequencies above 16.5 Hz to compensate for system roll-off above that point. The frequency response plot of the buffet actuator can be found in Appendix A.

When the shaker system is powered up at the ECC, hydraulic fluid is ported to the actuator which is commanded to its neutral point. When under software control, the buffet routine outputs a commanded frequency and amplitude to each VFO, which

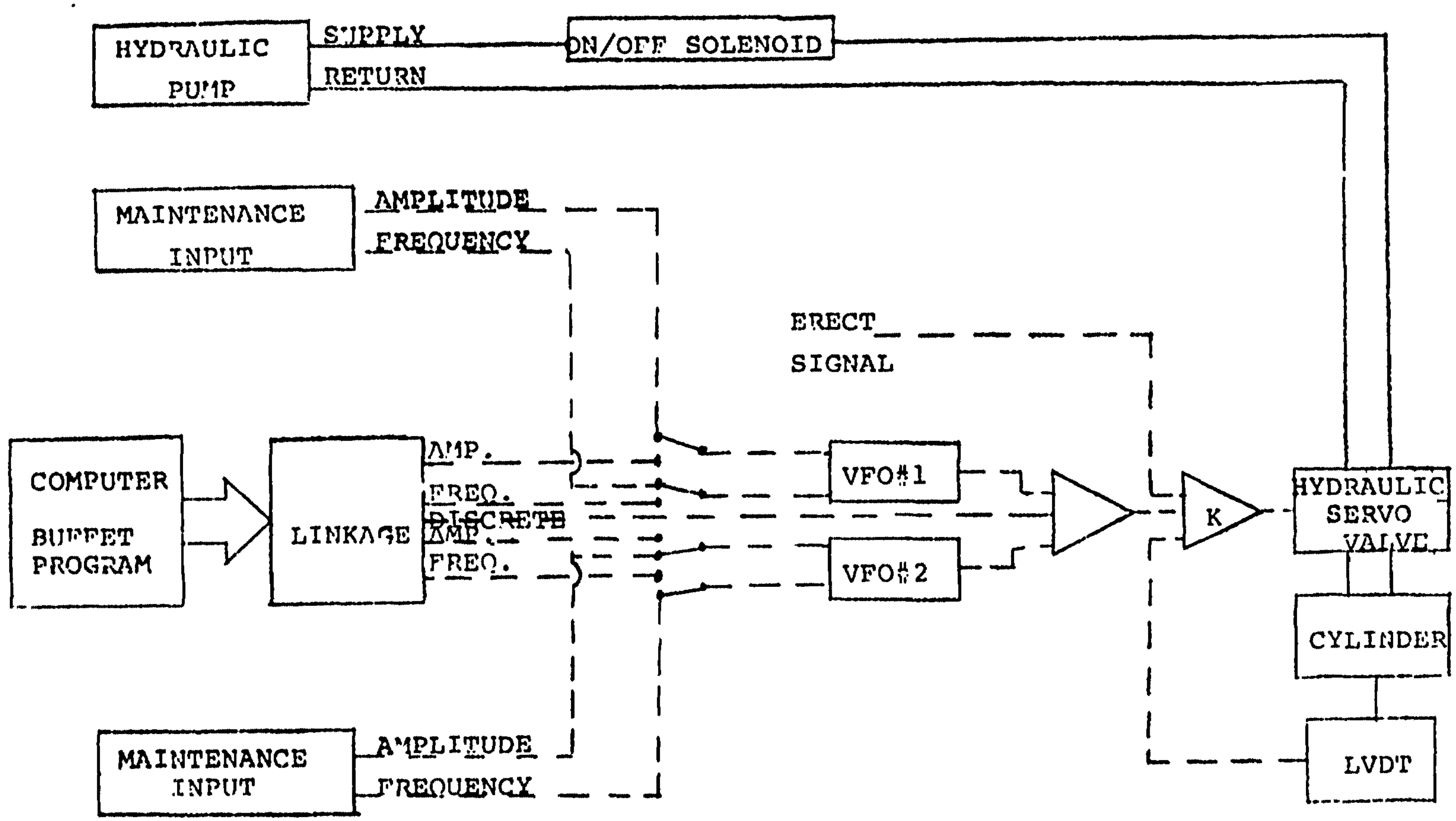


Figure 16. Seat Shaker System

construct the sinusoidal drive signal. In the maintenance mode, maintenance pots in the ECC can be used to input the frequency and amplitude commands. In either mode, in order to power the shaker system, the seat must be occupied.

An integral part of the shaker system is the vibration monitoring and protection system, VIBCOUNT. An accelerometer located in the seat pan cushion measures the seat vibration, filters the output into six frequency ranges, and passes this information to a software routine which calculates the user's vibration exposure. If the exposure factor exceeds the vibration safety limits as specified in MIL-STD-1472, the shaker system is shut down. This seat shaker mechanism, like the ALCOGS G-suit mechanism, is being implemented in several other simulator programs, including the F-4E G-seat retrofit and the Blackhawk helicopter simulator.

3.2.4 Electronic Control Cabinet

The electronic control cabinet contains all the electronics necessary to drive the G-cuing System. The development of the ECC for ALCOGS represents a first for G-cuing systems. The idea originated from the cabinet developed for Link-built platform motion systems, which houses the control electronics for the system. Incorporated within the cabinet are the power supplies, circuit cards for all sixteen servo drives, and the control logic to power up the seat. The seat is controlled from the front panel of the cabinet. Located here are switches to turn on the hydraulic and pneumatic pumps, power up the seat, suit, and shaker systems, and ramp in the drive signals to the hydraulic and pneumatic servos.

The seat is capable of operating in two different modes determined by the position of a key switch on the front panel. In the peripheral mode, the system accepts commands through the computer I/O linkage. In the maintenance mode, the system accepts commands from maintenance potentiometers located on the circuit cards or through external signals input directly to the servo circuit cards. The maintenance mode allows work to be done on individual drives without affecting any other part of the system.

In addition to being able to drive any actuator in the maintenance mode, the motion of each actuator can be displayed on the G-Cuing System Monitor. This is a portable device that is connected to the electronics cabinet. Not only can actuator motion be displayed, but the user can monitor firmness bladder, anti-G suit, and pneumatic accumulator pressures. In addition, the user can monitor seat position in terms of the four degrees of freedom, X, Z, θ and ϕ, for both seat pan and backrest cushions.

3.2.5 Modification of T-38 Simulator Cockpit

In June 1977, Link received from AFHRL a T-38 simulator cockpit, which was intended to house ALCOGS. In order to accommodate the system it was necessary to rework the cockpit to allow the seat and aft frame to slide in and out of the cockpit from the rear. The air blower unit, the canopy and its counterbalances, and several structural members were removed. New structural members were welded in along with the rails for sliding the system in and out of the cockpit. With these modifications, ALCOGS can be easily removed from its test stand and operated in a cockpit environment.

3.3 Safety

The fact that the hydraulic actuator assemblies can develop hundreds of pounds of force has caused a great deal of thought to be given to safety in the design of ALCOGS. Several areas of concern were addressed.

First, an interlock inhibits the seat from erecting to its neutral point upon powering up if the seat is occupied. This prevents someone from sitting in the seat, buckling up the lap belt, and then erecting the seat, which would force the lap belt tighter around the user's midsection. A LED on the ECC front panel indicates if the seat is occupied. Both the LED and interlock are activated by pressured sensitive switches on the seat pan and backrest top planes.

Another concern was that of a foreign object becoming trapped between the moving surfaces of the seat pan and backrest top planes and the seat frame. Pressure activated tape switches line the areas where an item, such as a finger, might stray. The switches trip at an applied force of 12 ounces, causing the system to go into an emergency shutdown. This problem is somewhat diminished by the fact that all moving elements are confined within the upholstered seat pan and backrest cushions. There are no moving parts, with the exception of the shaker actuator, outside the seat frame.

All the hydraulic actuator assemblies were designed such that in emergency shutdown, whether activated by the trip of a safety switch or the EMER OFF switch, any actuator can be extended immediately to free anything trapped. Upon emergency shutdown, the hydraulic supply is immediately dumped to return. A check valve in each actuator assembly allows the actuator to be manually pulled in extension, regardless of the position of the servo valve spool at shutdown.

4.0 ALCOGS SOFTWARE

4.1 General

The software used to drive the G-Cuing System represents a powerful research tool. By altering control parameters in each software program the various drive modalities can be altered to obtain totally different overall drive schemes. The characteristics of each modality can be altered while in the real-time mode. This gives the experimenter highly flexible, general purpose software with which to work.

4.2 G-Seat Software

4.2.1 Basics

The G-seat software makes use of the simulated flight translational and rotational accelerations transferred from the aircraft center of gravity to the pilot station as the basis of its computations. Aircraft rotational acceleration manifests itself as induced translational acceleration, which is added to the pure translational acceleration components; $\ddot{X}$, $\ddot{Y}$, and $\ddot{Z}$. These three translational accelerations then form the primary input to the G-seat drive. The drive is augmented, however, with another input of either aircraft roll acceleration or roll rate, selectable by the user. Because of the small moment arm between the pilot station origin and the aircraft roll axis, the software can accept and display roll effects directly, rather than depending on the manifestation of roll effects as induced translation.

One of the fundamental concepts in formulating the G-seat software is that aircraft acceleration corresponds to seat position. The seat is composed of excursion devices, and this concept simply implies that maximum seat excursion is then reserved for some predetermined maximum aircraft acceleration. In the 1G state, the bladders are inflated to a pressure that corresponds to the threshold of contact of the buttocks with the passive tuberosity blocks and of the central back region with the backrest top plane. From this point the bladders are driven only in deflation, causing the areas of the central back region and ischial tuberosities in the buttocks to be subjected to increased pressure.

4.2.2 Drive Concepts

The software drive concepts that follow represent the initial drive configuration. These concepts can be easily altered to produce totally different drive schemes. The axis system referred to herein is the pilot station axis system shown in Fig. 17.

4.2.2.1 Seat Translation

The seat pan top plane translates up and down as function of Z-axis acceleration. Positive acceleration (negative G's) produces increased top plane elevation. Negative acceleration (positive G's) results in decreased top plane elevation. The seat pan top plane also has the capability of translating fore and aft as a function of X-axis acceleration. For positive X acceleration (thrusting) the top plane translates forward, and for negative X acceleration (braking) the top plane translates aft. This provides a scrubbing cue of the buttocks against the seat cushion.

The backrest top plane translates as a function of X-axis acceleration. For positive acceleration, the backrest top plane translates forward. For negative acceleration, the top plane translates aft. This changes the effective point of rotation for the orientation drive described below.

4.2.2.2 Seat Plane Orientation

The seat pan and backrest planes re-orientate in the seat pitch and roll axes. The seat undergoes pitch attitudinal changes for X-axis acceleration inputs. For positive acceleration, the seat pan pitches up, and the backrest pitches bottom forward, top aft. The orientation reverses for negative X-axis acceleration.

Orientation changes due to Y-axis acceleration occur in a manner normal to the acceleration vector. However, as maximum excursion is scaled to maximum anticipated acceleration, the surface planes are not normal to the acceleration vector, but to a scaled version of the vector. The sign convention is identical for seat pan and backrest planes.

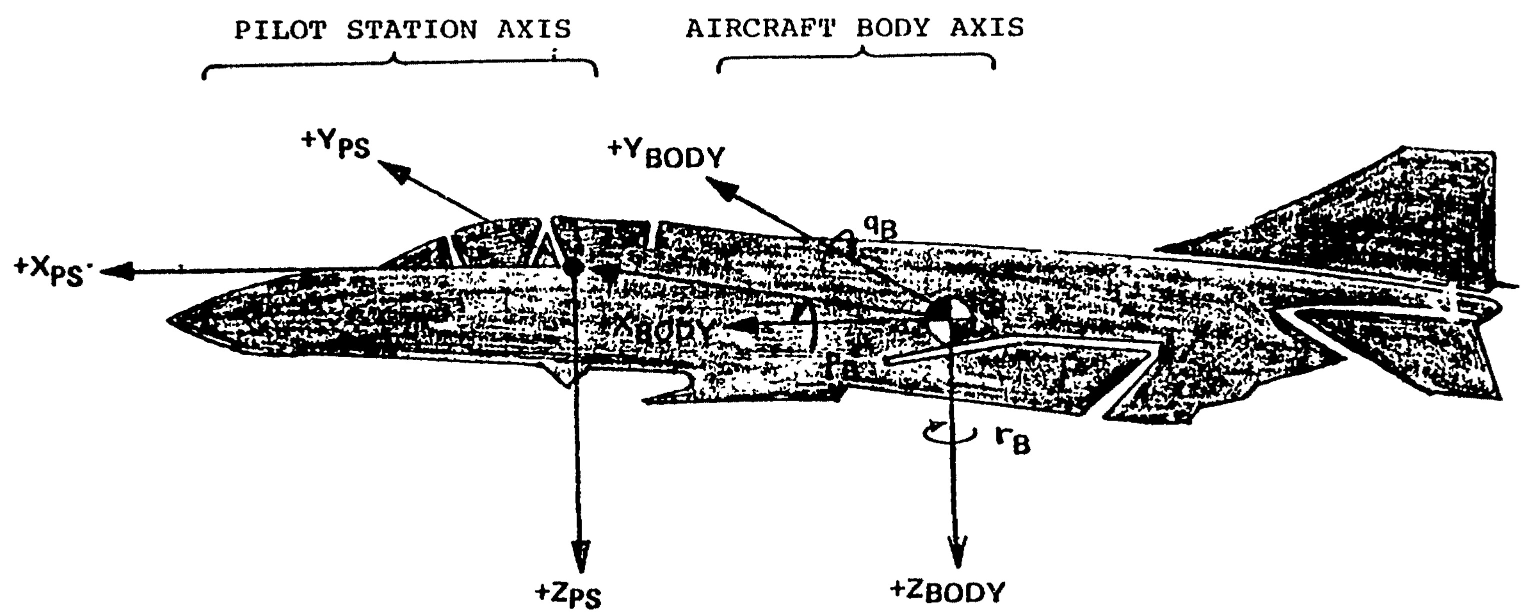


Figure 17. Pilot Station Axis System

4.2.2.3 Roll Augmentation

As previously mentioned, special consideration is given to display roll effects. The experimenter can select either roll acceleration magnitude or roll velocity magnitude as a roll input to the various drive concepts. This input forms a part of the seat orientation drive in addition to being part of the drives mentioned below.

4.2.2.4 Radial Elements

The radial elements are driven such that the wings traverse an arc of 0 to 50 degrees in relation to the backrest top plane. The position of the wings is a function of X- and Y-axis accelerations and roll augmentation input. These motions provide an increased area of contact cue in the vicinity of the lower back.

The two wings are driven together from their neutral point in proportion to the magnitude of the X-axis acceleration. For positive acceleration, the angle between the wings and backrest increases. For negative acceleration, the angle decreases.

For Y axis and roll inputs the wings are driven differentially. The angle of one wing increases as the angle of the other decreases. The wing angle has an opposite sign relationship to backrest orientation.

4.2.2.5 Firmness Bladders

The pressure in the seat pan and backrest firmness bladders is varied as a function of simulated aircraft acceleration. The pressure in the bladders is varied unidirectionally; the pressure is decreased from the neutral point. Inflation above the neutral point does not occur. The neutral point is defined as that pressure corresponding to the threshold of contact between the pilot's body and cushion top planes.

As the simulated aircraft experiences increasing load, the pressure in the bladders decreases. For vertical acceleration (positive G's) both cells of the seat pan bladder simultaneously deflate. This produces two distinct effects. More of the seat pan top plane comes into flesh contact. This contact is particularly noticeable due to the presence of the thigh ramps. In addition there is buttocks pressure redistribution, emphasized by the presence of the tuberosity blocks. Longitudinal acceleration response is manifested as a decrease in the pressure of the backrest bladder. Lateral accelerations and roll inputs cause one cell of the seat pan firmness bladder to deflate while the other cell remains at the neutral point. Rightward seat acceleration causes the left cell to deflate. The reverse is true of leftward acceleration.

For all three of the above cases the pressure within the firmness bladders is in proportion to the magnitude of the acceleration. The sign convention for the backrest is the opposite of that of the seat pan. Positive X-axis acceleration causes the backrest bladder to deflate while negative Z-axis acceleration causes the seat pan bladder to deflate. In all cases, bladder deflation is a major contribution to the feeling of "settling into the seat."

4.2.2.6 Lap Belt

The lap belt drive is composed of four inputs. First is the orientation of the external force acceleration projection onto the XZ plane relative to the seat axis. This includes the effect of the gravity component in the Z-axis acceleration. Both actuators are driven simultaneously from this input. For conditions of loss of lift or braking, the lap belt contracts. For conditions of increased lift or thrusting, belt extension occurs.

The second input is the orientation of the gravity vector projection onto the XZ plane relative to the seat axis. This causes the lap belt to contract as the seat and aircraft pitch over to a point where the pilot is inverted, and to relax again as an upright attitude is approached. Again, both actuators are driven simultaneously.

The positions of the seat pan and backrest top planes serve as the third input to the lap belt drive. The positions are used to calculate a factor that decouples cushion planar movement and lap belt movement.

The last input is a response to Y-axis acceleration and roll input. This causes a differential lap belt drive, one actuator extending while the other retracts. The sign convention is opposite to that of the seat roll orientation sign convention. This creates a scrubbing effect across the pilot's midsection as the aircraft experiences lateral acceleration or rolls right or left.

These four inputs form the composite lap belt drive. This drive can be altered by varying the weighting factor associated with each input, allowing the experimenter to evaluate the lap belt drive concepts.

4.3 Anti-G Suit Software

The software drive for the G-suit is calculated in its own module. As the pilot "pulls G's", suit inflation is commanded in proportion to the magnitude of the acceleration. For negative G's, the suit remains at its deflated state. A variable psi/G instructor input is available through a switch on the ECC front panel and is not a part of the software control. The G-suit pilot press-to-test capability is implemented totally in hardware and makes no demands on the software.

4.4 Shaker Software

The ALCOGS shaker software is primarily composed of two separate modules. The first is the buffet program which calculates the amplitude and frequency of the appropriate vibratory cues. The other routine is the VIBCOUNT software. This module calculates the user's vibration exposure factor and shuts the shaker system down if the permissible exposure is exceeded.

4.4.1 Buffet Program

This module takes as inputs various measures of the aircraft state, such as airspeed, angle of attack, and engine thrust, along with aircraft control surface positions. From this information, the module computes the amplitude and frequency of the appropriate continuous vibratory cues and the amplitude of the appropriate discrete cues.

The shaker system utilizes two VFO's to output the continuous vibratory cues. The potential exists in the program to have six different continuous cues. So a decision has to be made as to which frequencies and amplitudes should be output to the two VFO's. A hierarchy is established, which can be varied by the experimenter, and the amplitudes of the continuous cues are scaled accordingly. The two cues with the greatest magnitudes are the basis for the VFO signals. These are modified, however, by a mixing strategy that utilizes the energy in each of the six continuous cues to adjust the frequency and amplitude of the two basic cues. These modified signals are then used to create the VFO sinusoidal outputs.

The discrete cue is a pulse input to the shaker, which manifests itself as a "bump." The amplitudes of the various discrete cues are additive, up to a maximum amplitude limit.

4.4.2 VIBCOUNT

The VIBCOUNT routine examines output of six bandpass filters applied to the signal of an accelerometer mounted in the seat pan cushion. Based on the magnitude of the accelerometer outputs, within each frequency band a computation is made according to the vibration safety limits called out in MIL-STD-1472 to determine a user exposure factor. When the exposure factor reaches a value of 1.0, VIBCOUNT outputs a signal disabling the shaker system for that particular user. The exposure factor will decay from a maximum value of 1.0 to its minimum value of 0.0 over a period of twenty-four hours.

The user exposure factors for up to a dozen subjects are stored on file and updated every time a subject signs on the system. A continuous update is effected for the particular subject presently using the system. Modified versions of the VIBCOUNT routine have been used on other simulator programs, including the Space Shuttle Simulator for NASA.

4.5 Research Control

Each of the basic ALCOGS drive concepts contains control parameters by which the experimenter can alter and evaluate any of the above drive philosophies. These control parameters give the experimenter the following concept control:

1) Inclusion or deletion of individual concepts to the overall drive scheme.
2) Alteration of the proportionality or scale factor of excursion to acceleration through manipulation of maximum expected acceleration and/or allocated actuator excursion.
3) Reversal of sign convention of each concept.
4) Increase or decrease the importance of each input to a drive concept through alteration of the drive mixing constants.
5) Establishment of acceleration thresholds below which there is no seat response, and acceleration distortion to emphasize particular regions of the acceleration profile.
6) Bias addition to the neutral points of the radial elements and firmness bladders.
7) Alternation of the drive concepts to account for seat angle.

5.0 Preliminary Observations

While the G-Cuing System was in-house at Link's Binghamton facility (September 1977) some preliminary testing was performed in reference to the cuing strategy to be employed in the software. One area of investigation was the longitudinal actuator drive. This drive could be implemented in either of two ways. The first implementation was as a translational cue. The seat pan top plane could be driven in response to X-axis acceleration with the opposite sign as the acceleration vector. The top plane would move forward under deceleration and aft under thrusting conditions. The second implementation used the top plane to provide a scrubbing cue. The seat pan top plane responds to X-axis acceleration with the same sign to that of the acceleration vector, just the reverse of the first implementation. This latter cuing scheme was thought to provide a much better cue and is incorporated in the initial software configuration.

The lap belt differential drive was found to contribute a surprisingly strong cue. This drive scheme provides a scrubbing cue across the pilot's midsection under roll and Y-axis acceleration and is augmented by the passive shoulder harness attached to the lap belt. This particular cue, along with the longitudinal scrubbing, is not available in the first generation seat.

The capability to generate buffet cues through the seat pan cushion actuators rather than the seat frame shaker has been provided on ALCOGS and is controlled by a switch in the ECC. Should the buffet cues generated by the seat pan actuators be judged of comparable quality to that generated by the seat shaker, additional seat pan actuator life testing must be conducted to determine life within the high frequency short stroke environment prior to the exclusive generation of buffet cues through the seat pan actuators.

During assembly, installation and acceptance the author has had occasion to remove individual actuator sub-assemblies and the cushion assemblies from the seat for demonstration and trouble-shooting. The author has found the modular assembly design to be invaluable in terms of ease manitainability. The modular assemblies simplify actuator removal and repair, and minimize system downtime. Should ALCOGS-like G-cuing systems become a part of current or future simulators, entire seat pan or backrest assemblies could be spared in case of a G-seat failure. Within minutes the failed assembly could be removed for repair and its spare installed.

Once the software was integrated with the hardware and used to drive the system, another problem manifested itself, although not an unexpected one. A stepping effect is noticeable in actuator motion due to the 20 iteration per second program iteration rate of the STARS. ALCOGS, displaying a 10 Hz bandpass, is capable of responding to the discrete digital changes in actuator drive signals at the program iteration rate. Anticipating this problem Link designed and incorporated variable bandpass filters as part of the input signal path to each servo which function in series with the high bandpass filter section of the linkage D/A circuit. The filters smooth the computer-originated drive signal such that the stepping in the actuator motion is eliminated. The filters are variable so that the bandpass can be increased as the iteration rate is increased as per the Air Force Human Resources Laboratory research plan. As set up during installation, the filters were adjusted for a 2.5 Hz bandpass, yielding a servo bandpass of approximately 2.0 Hz. As the program iteration rate is increased, the variable bandpass filters can be rolled out and overall servo bandpass increased so the system can be utilized to its full potential.

6.0 Summary and Conclusions

The Advanced Low Cost G-Cuing System was designed and built to fulfill a need for a research system to investigate and determine optimal G-seat performance capabilities. The G-Cuing System consists of a G-seat, anti-G suit, and seat shaker system. All three of the above systems represent advances over the capabilities of present G-Cuing devices.

The cuing schemes employed in the ALCOGS G-seat differ from those of the first generation seat. The basic seat drive concept is the flat plate/firmness bladder concept, where the flat plates provide the skeletal attitude changes, and the bladders provide flesh pressure and flesh area of contact variations. The effectiveness of this concept has been demonstrated in experiments performed on the G-seats at the ASPT facility.

The original concept of driving the backrest top plate with pneumatically driven metal bellows had to be abandoned because of stability problems and lack of time allowed to solve these problems. Hence, both seat pan and backrest top plate drive systems consist of hydraulic actuators. The firmness bladders are pneumatic systems. The hydraulic actuators are all closed loop on position, and the firmness bladders are closed loop on pressure. All the seat servo systems, hydraulic and pneumatic, display a 30 millisecond rise time.

The G-suit system displays increased responses over previous systems due to increased pneumatic flow capability. A two-stage pneumatic manifold utilizing a vacuum exhaust was developed to provide the increased flow capability. (This manifold was ultimately used in the firmness bladder drive, in addition to the suit drive). An electronically implemented press-to-test feature is also part of the G-suit drive system.

The seat shaker operates over a 0 Hz to 40 Hz frequency range with 0.5g acceleration capability from 4.5 Hz to Hz. A new servo drive utilizing two variable frequency oscillators and a discrete "bump" channel was developed for the system. The vibration exposure protection system (VIBCOUNT) is incorporated, which deactivates the shaker system when the subject in the seat exceeds a predetermined accumulated vibration level.

ALCOGS provides the user the hardware/software flexibility for the investigation of optimal G-cuing designs and philosophies (Reference 5). In addition, the user has a system that has demonstrated ease of maintainability, which minimizes system downtime. However, the G-Cuing System has not yet been integrated with the T-38 cockpit, visual display and flight software. When this is done, the determination of appropriate response characteristics and cuing schemes can begin.

7.0 References

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APPENDIX A: FREQUENCY RESPONSE DATA

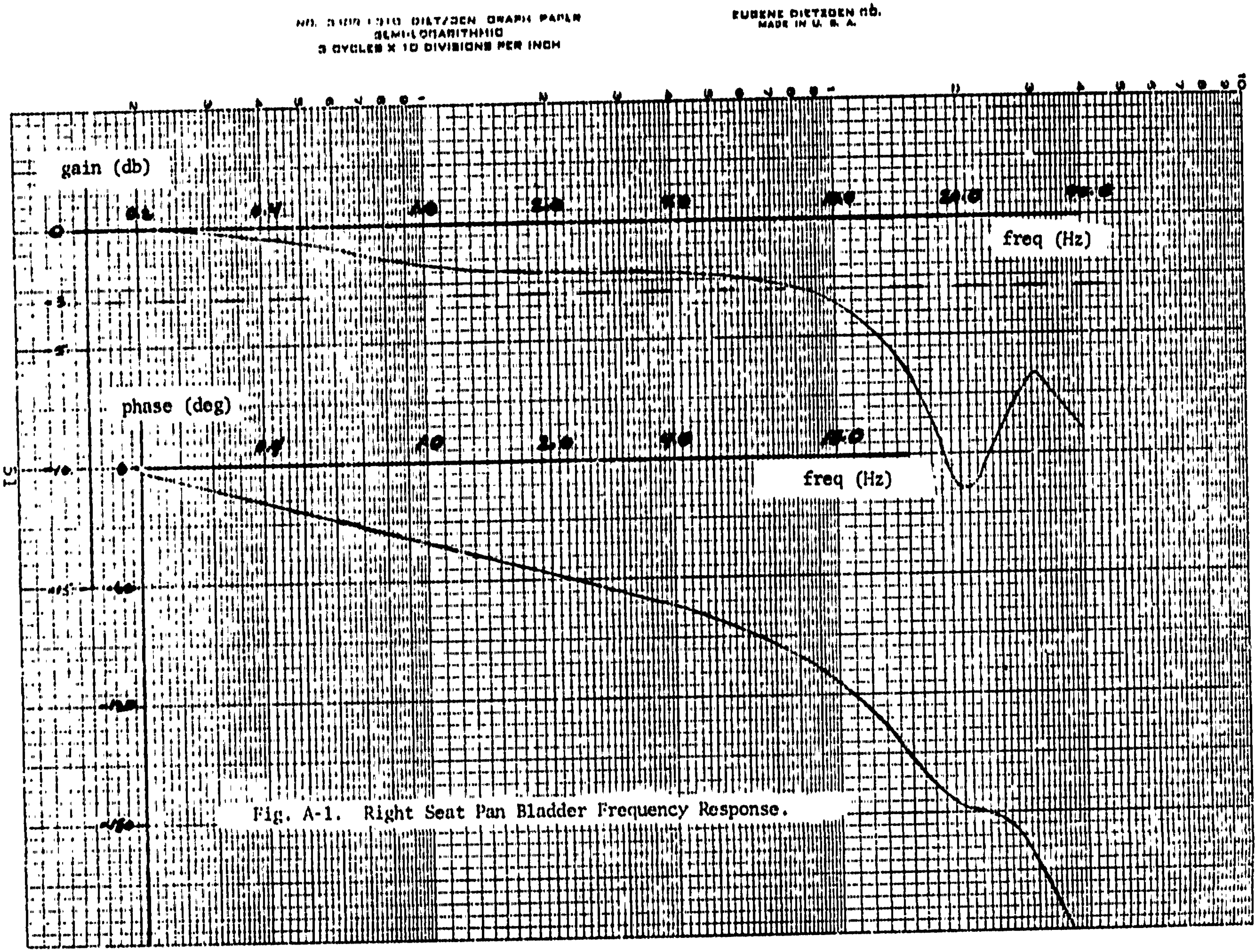

Fig. A-1. Right Seat Pan Bladder Frequency Response.

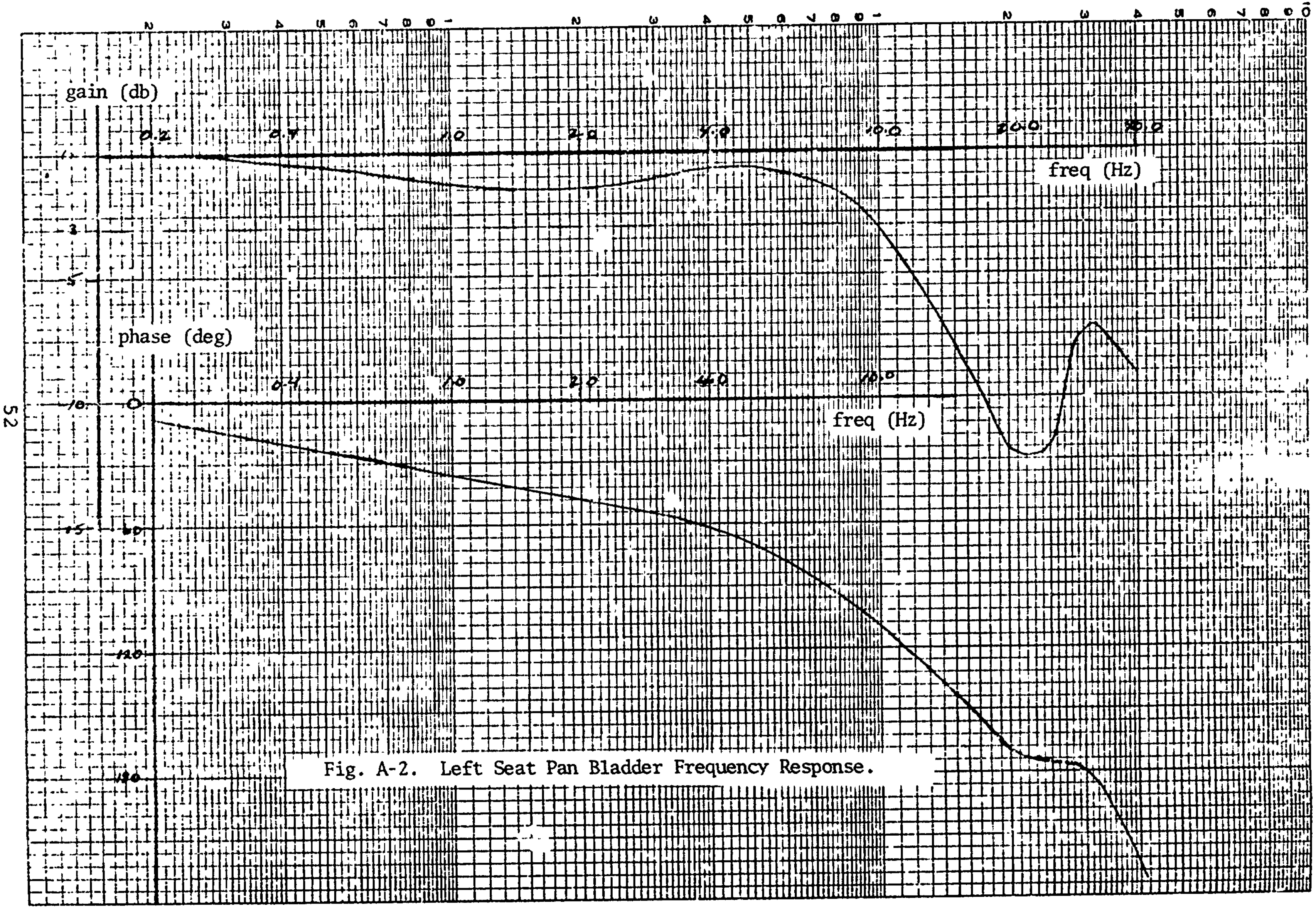

Fig. A-2. Left Seat Pan Bladder Frequency Response.

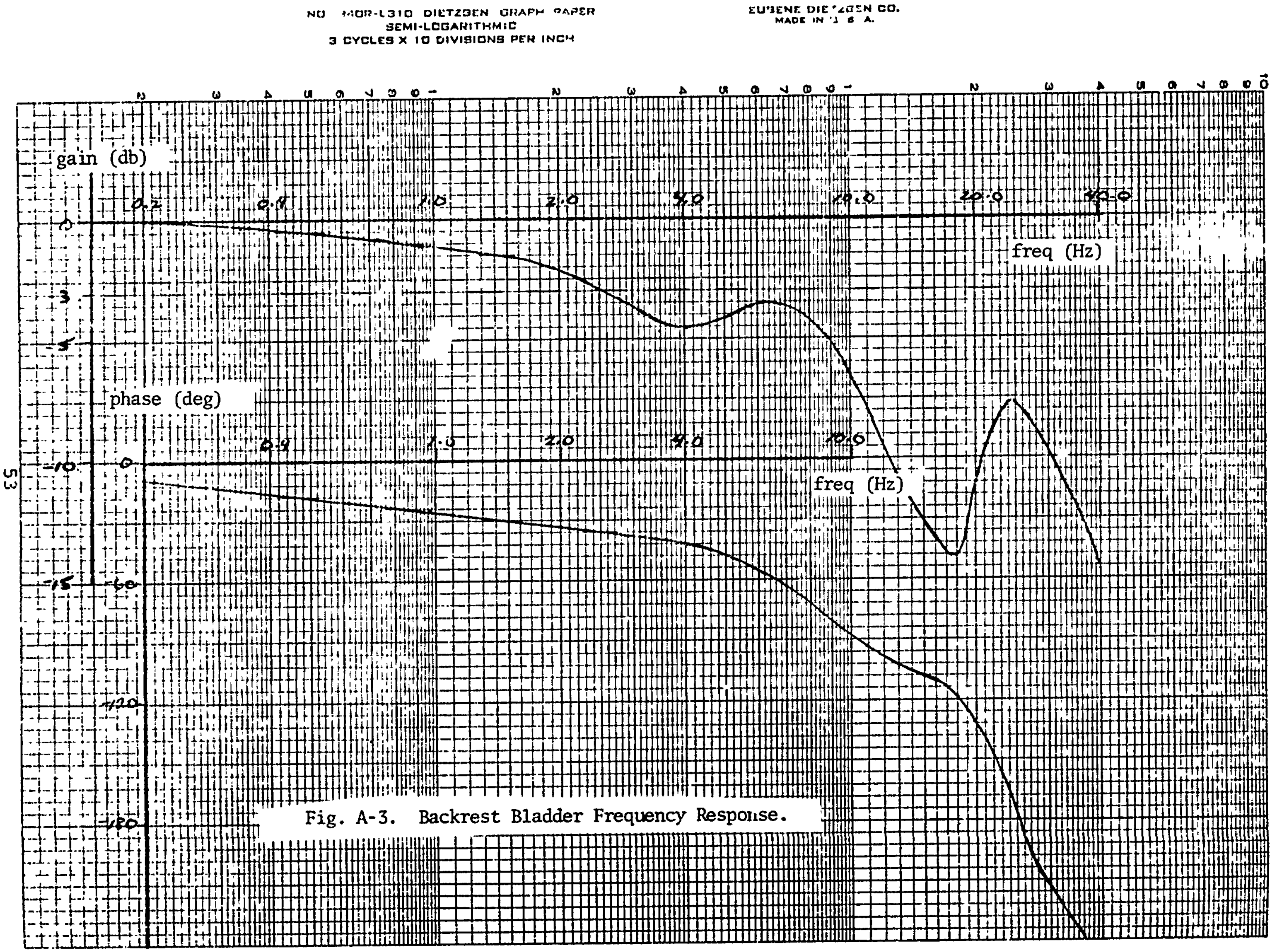

Fig. A-3. Backrest Bladder Frequency Response.

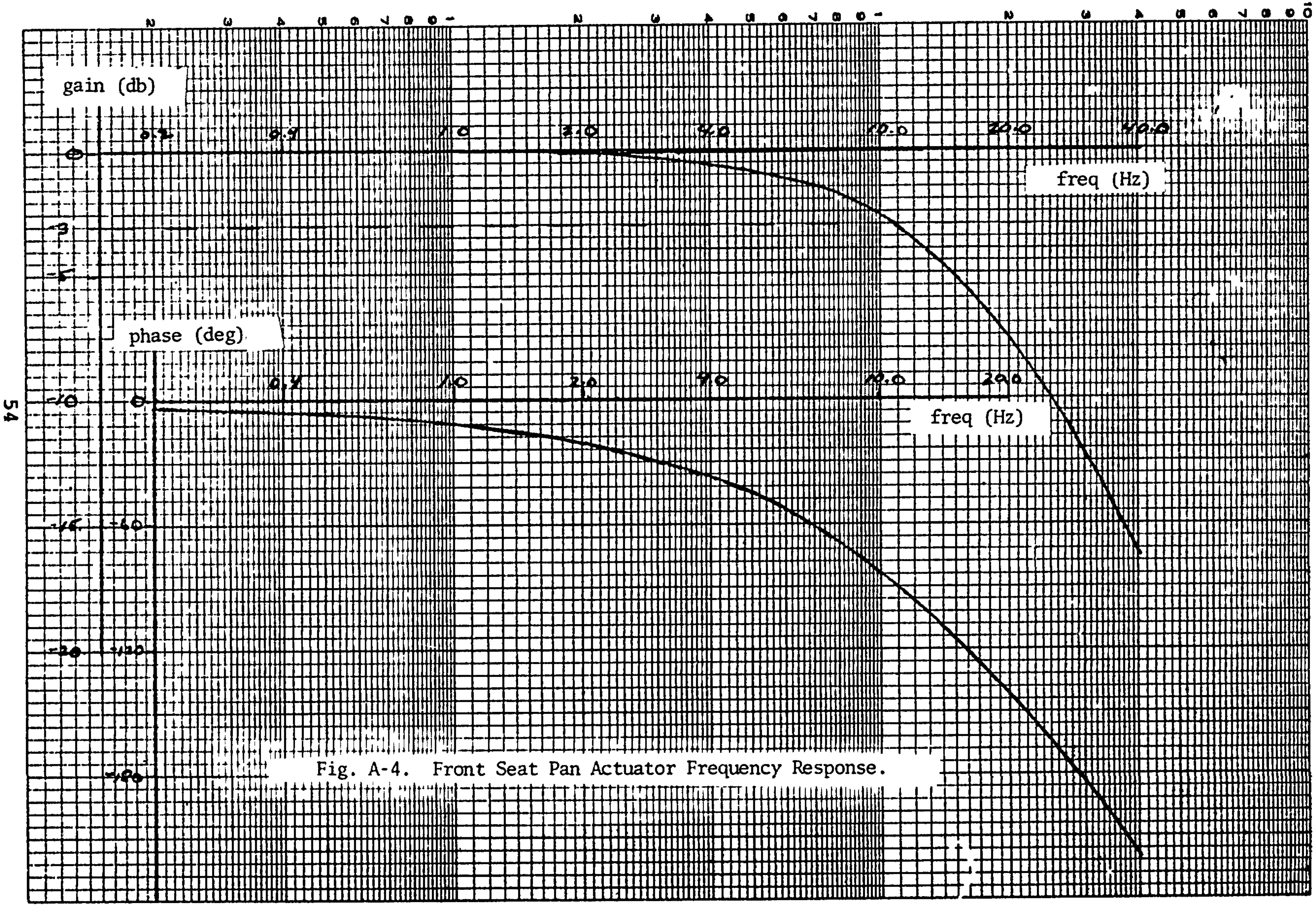

Fig. A-4. Front Seat Pan Actuator Frequency Response.

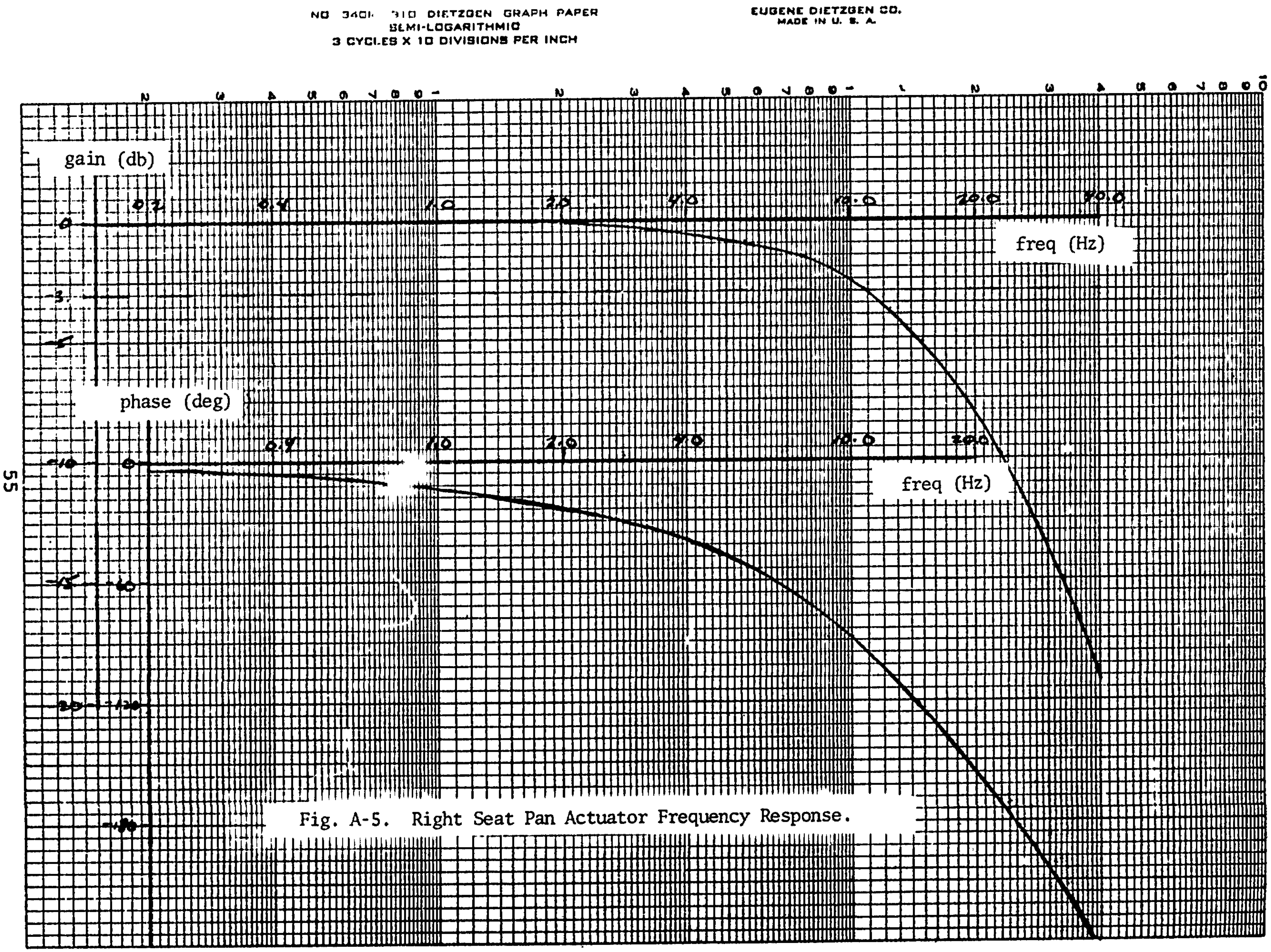

Fig. A-5. Right Seat Pan Actuator Frequency Response.

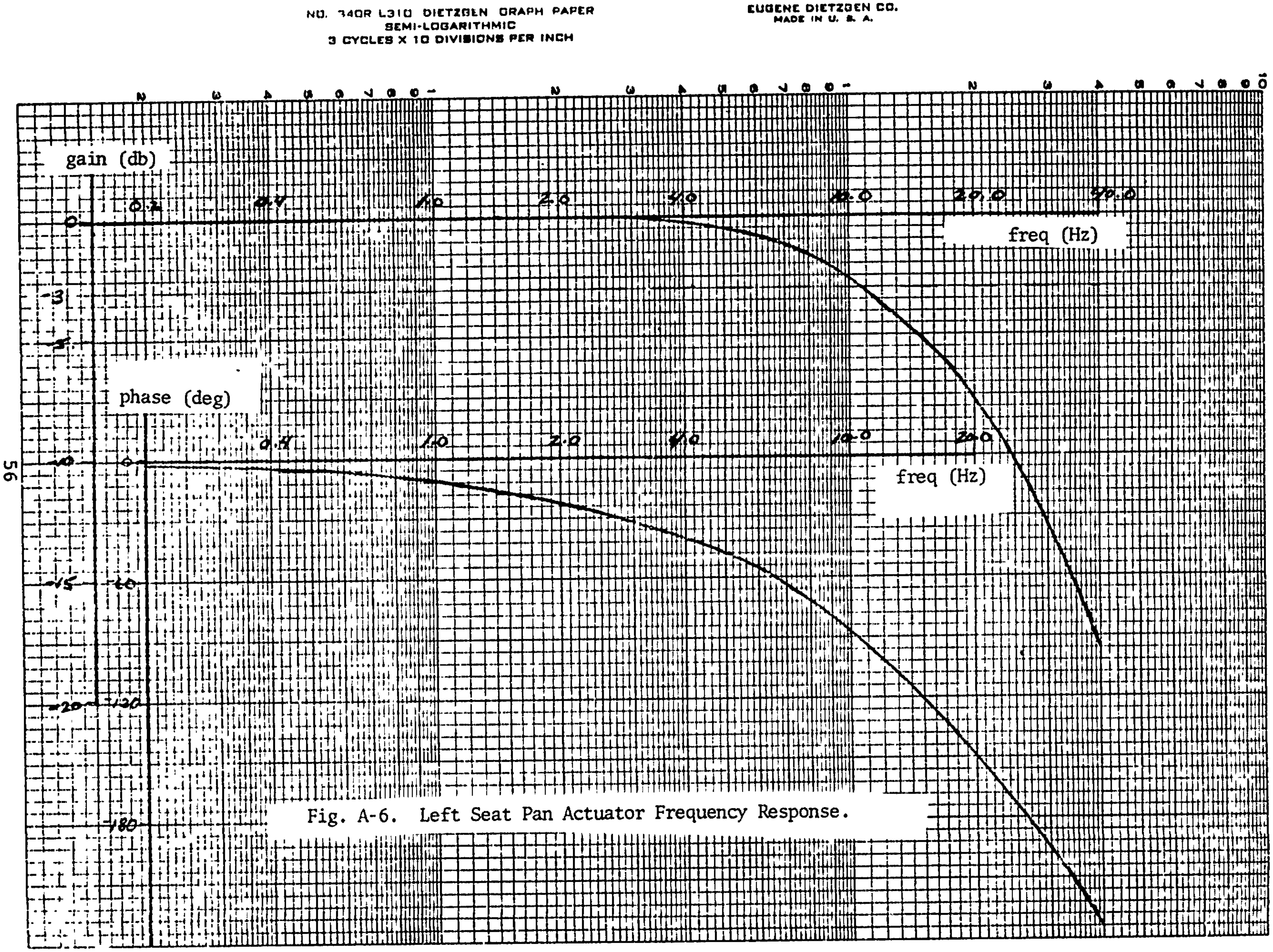

Fig. A-6. Left Seat Pan Actuator Frequency Response.

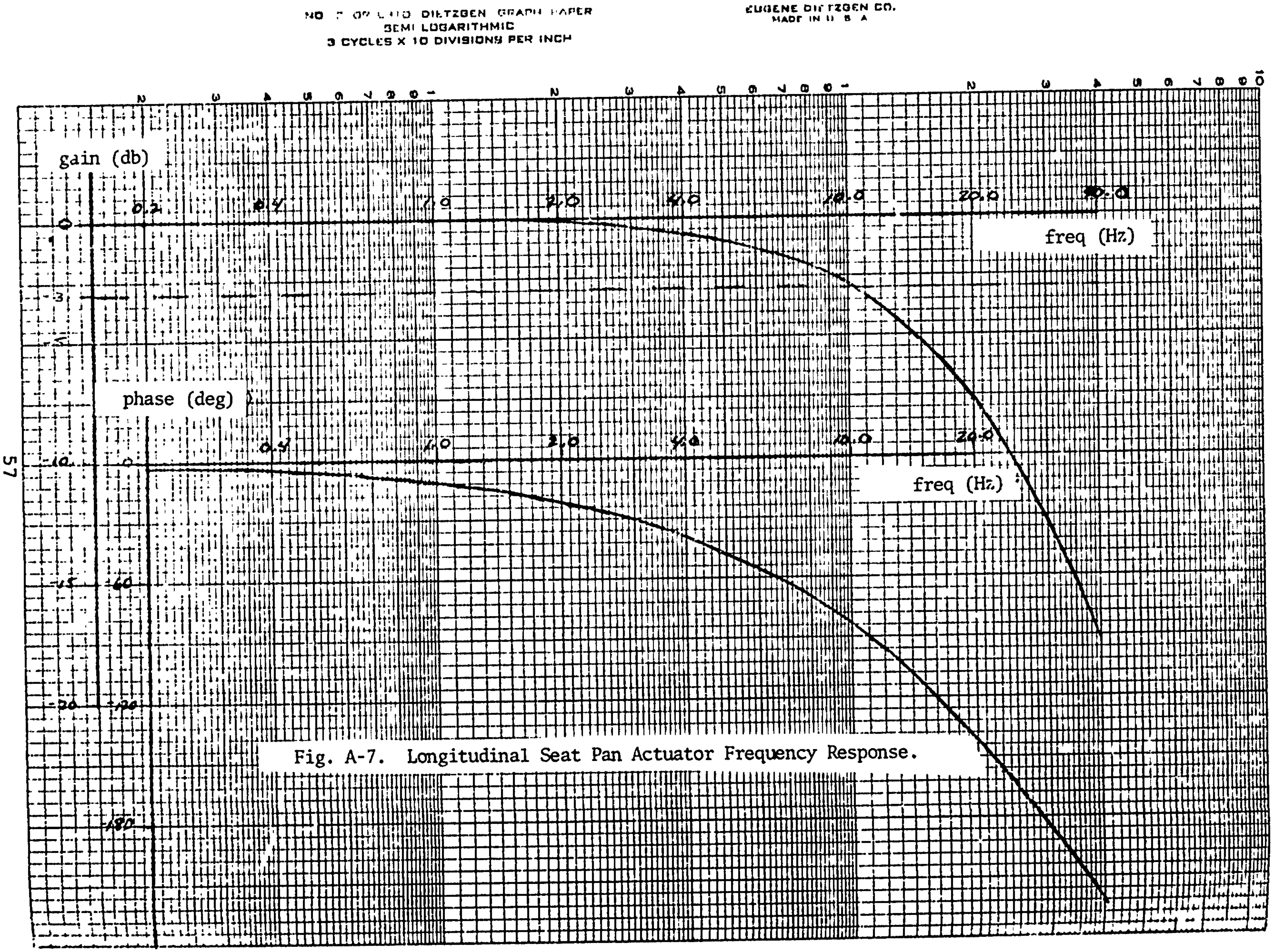

Fig. A-7. Longitudinal Seat Pan Actuator Frequency Response.

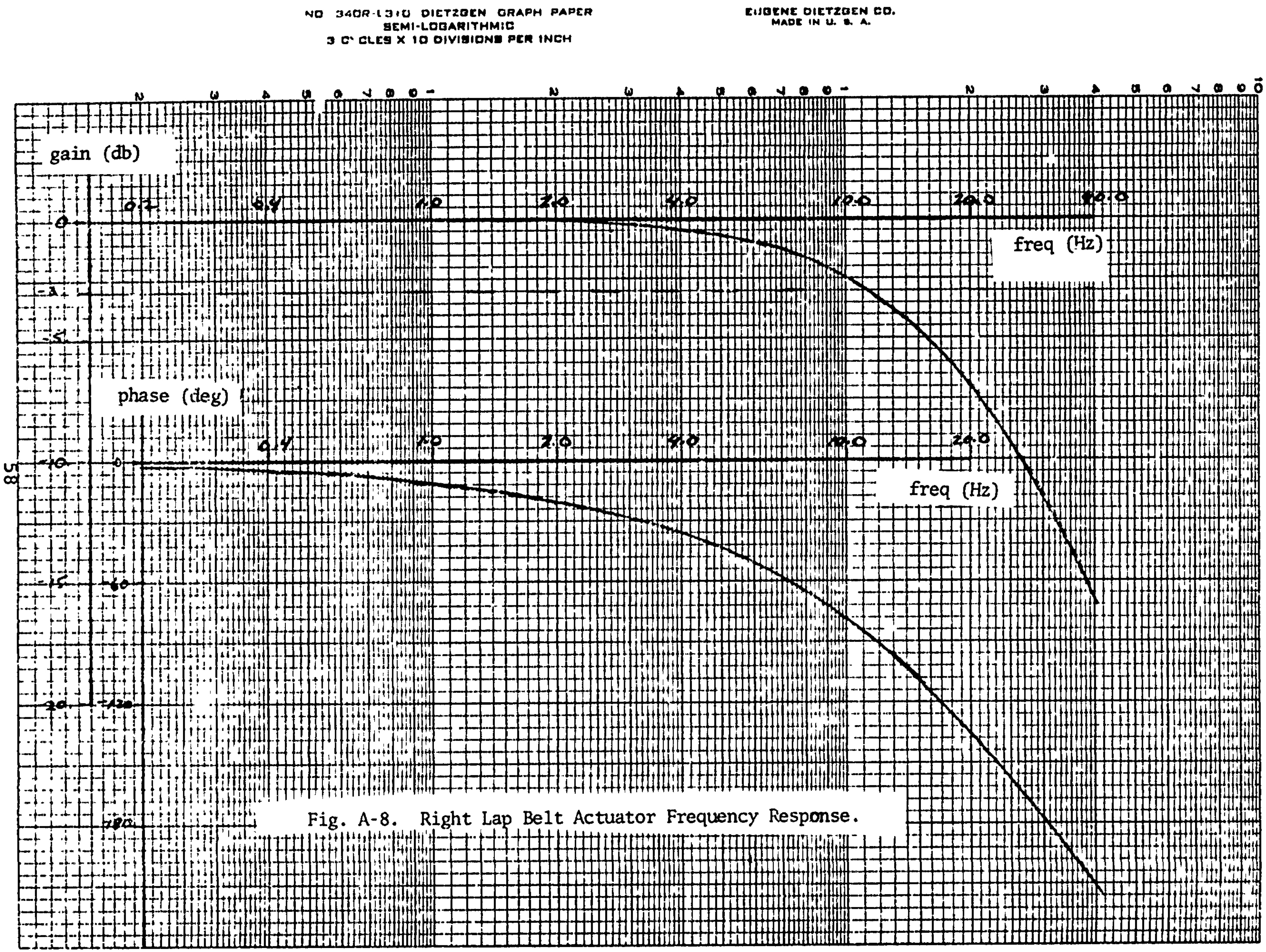

Fig. A-8. Right Lap Belt Actuator Frequency Response.

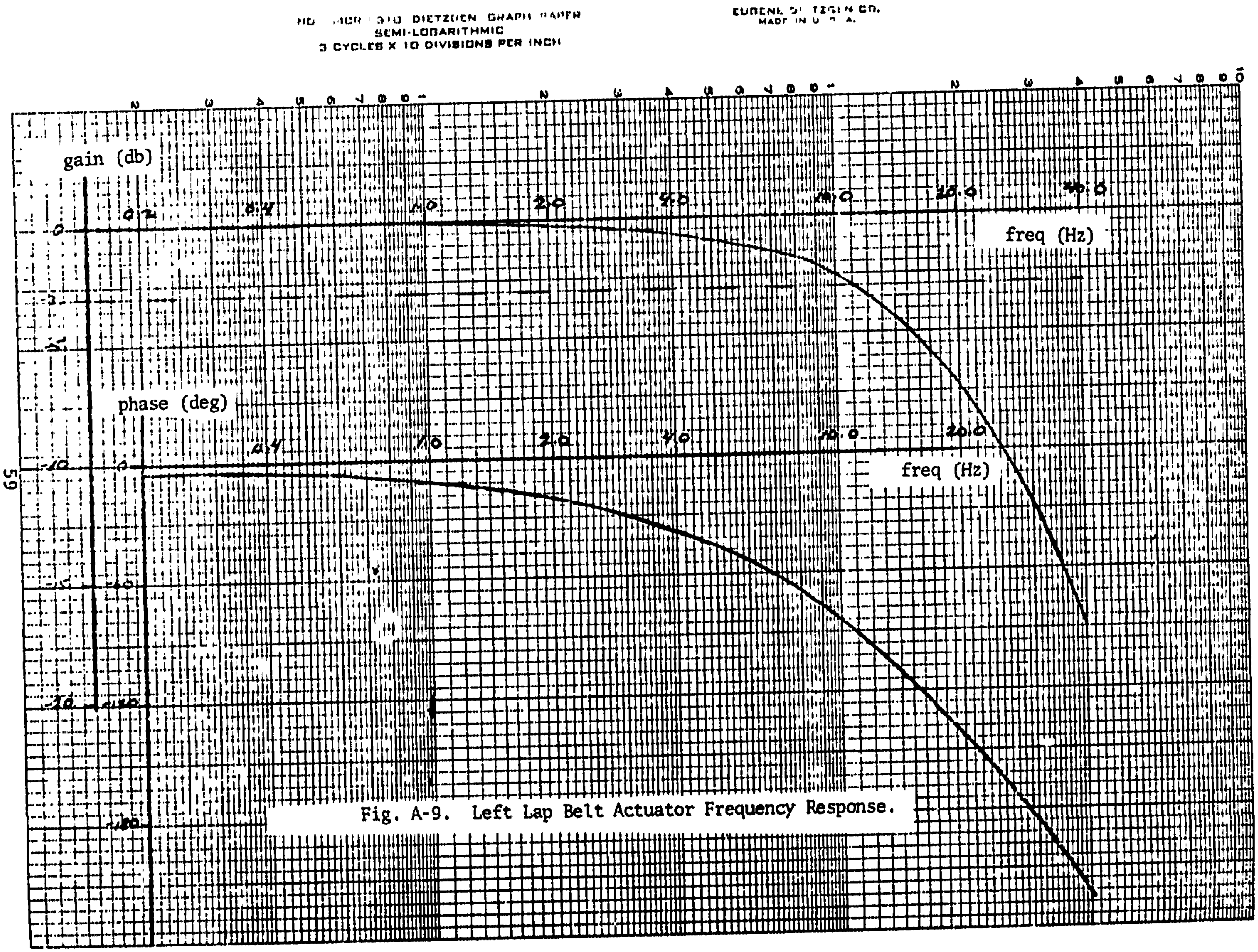

Fig. A-9. Left Lap Belt Actuator Frequency Response.

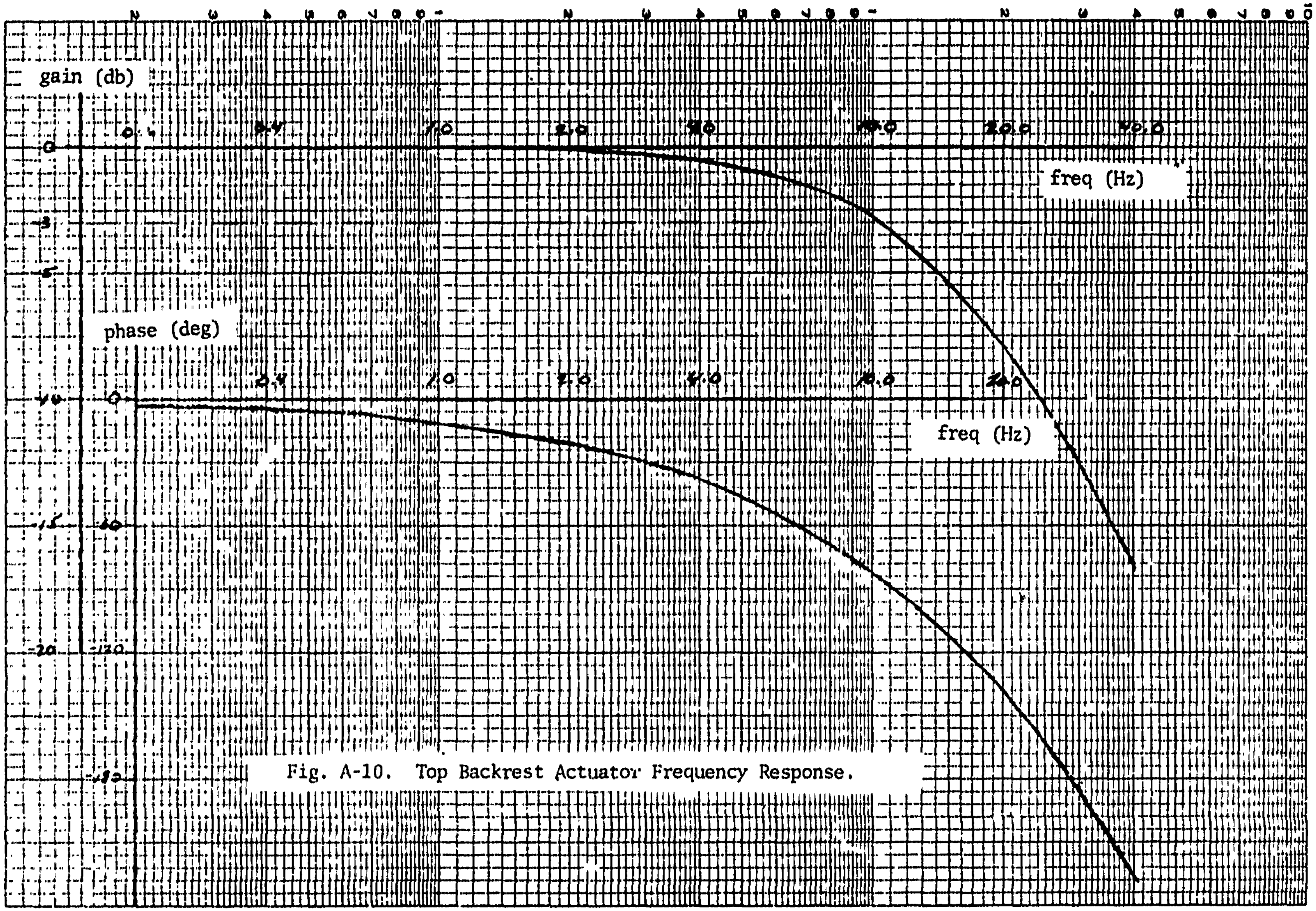

Fig. A-10. Top Backrest Actuator Frequency Response.

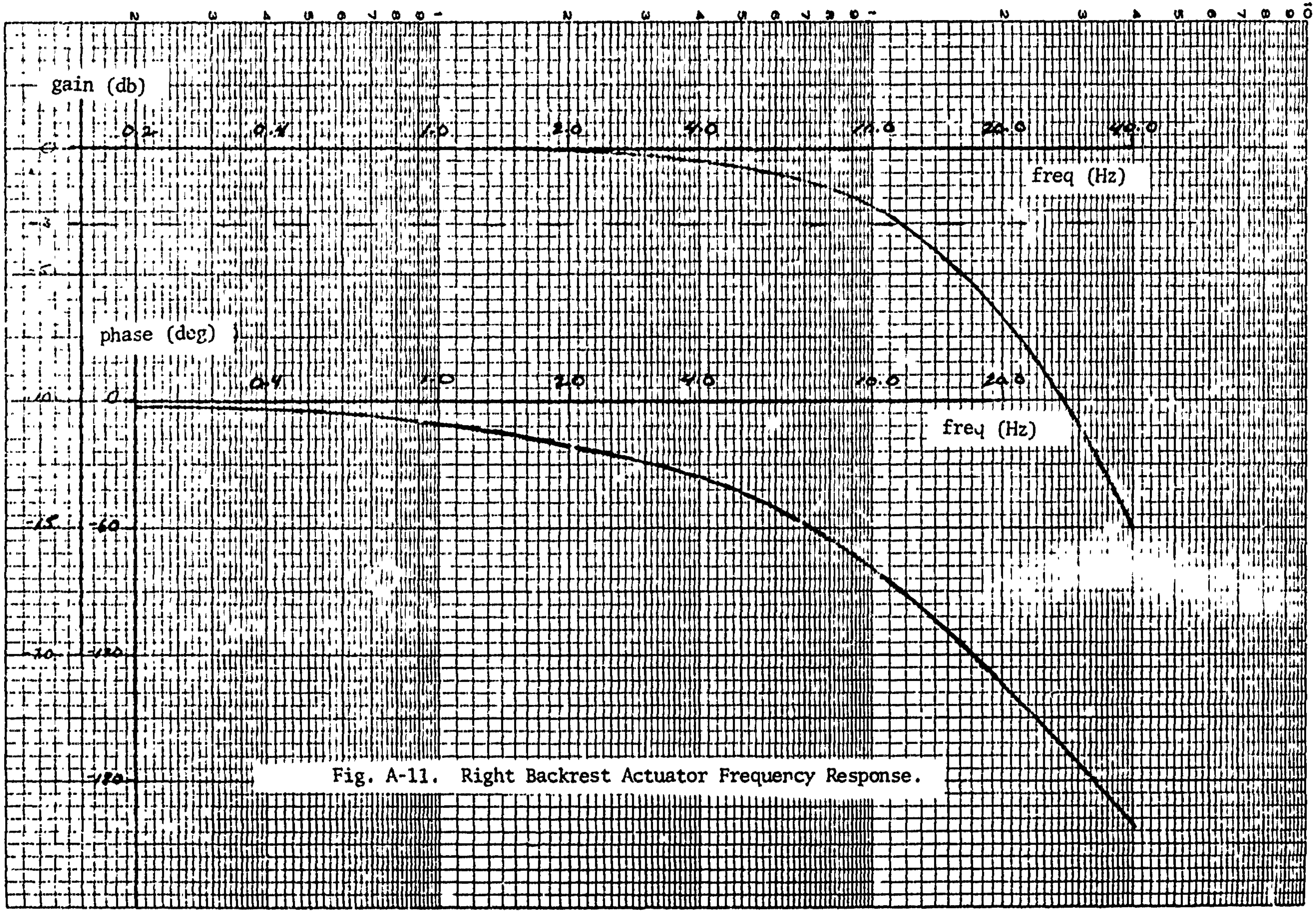

Fig. A-11. Right Backrest Actuator Frequency Response.

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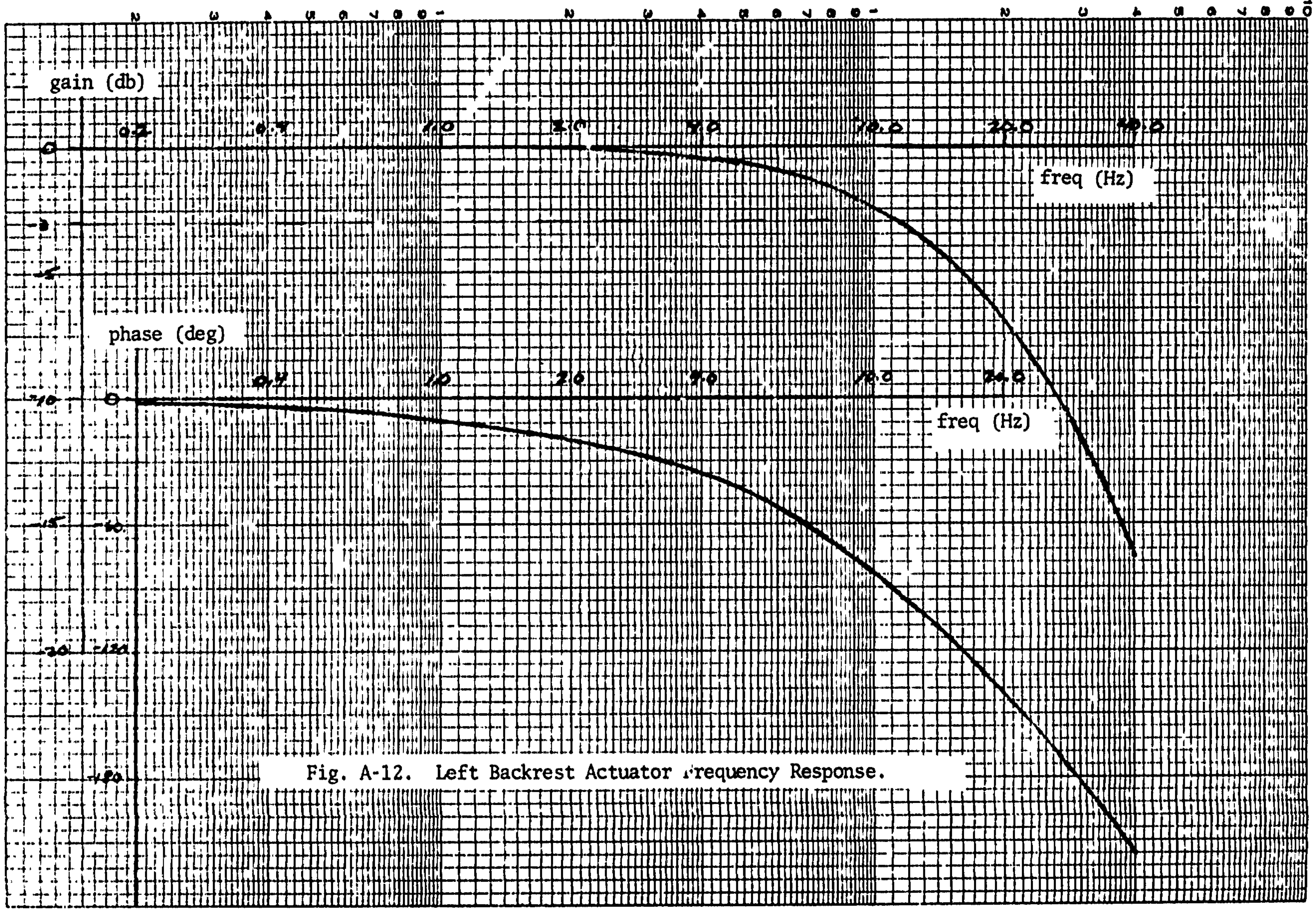

Fig. A-12. Left Backrest Actuator Frequency Response.

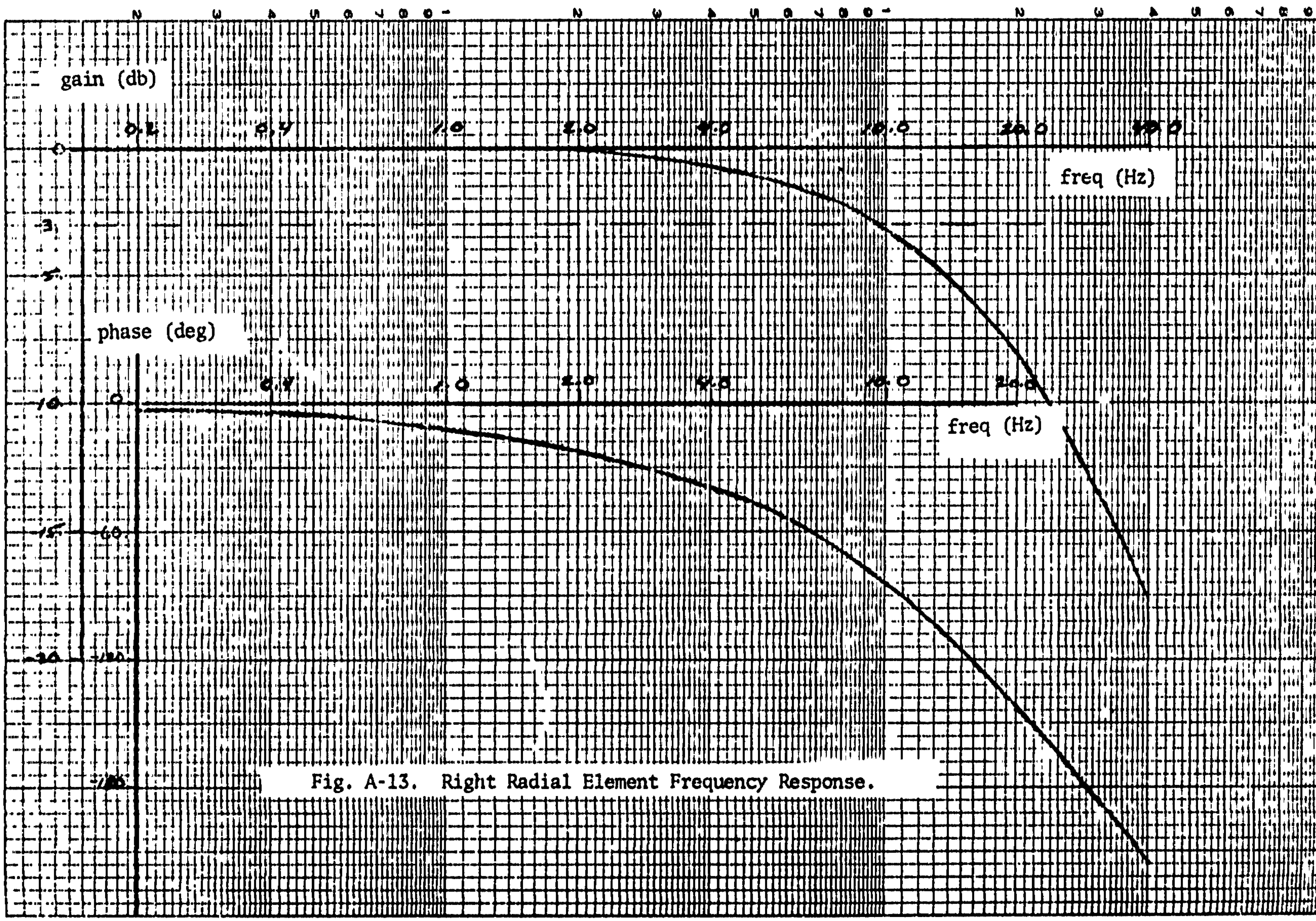

Fig. A-13. Right Radial Element Frequency Response.

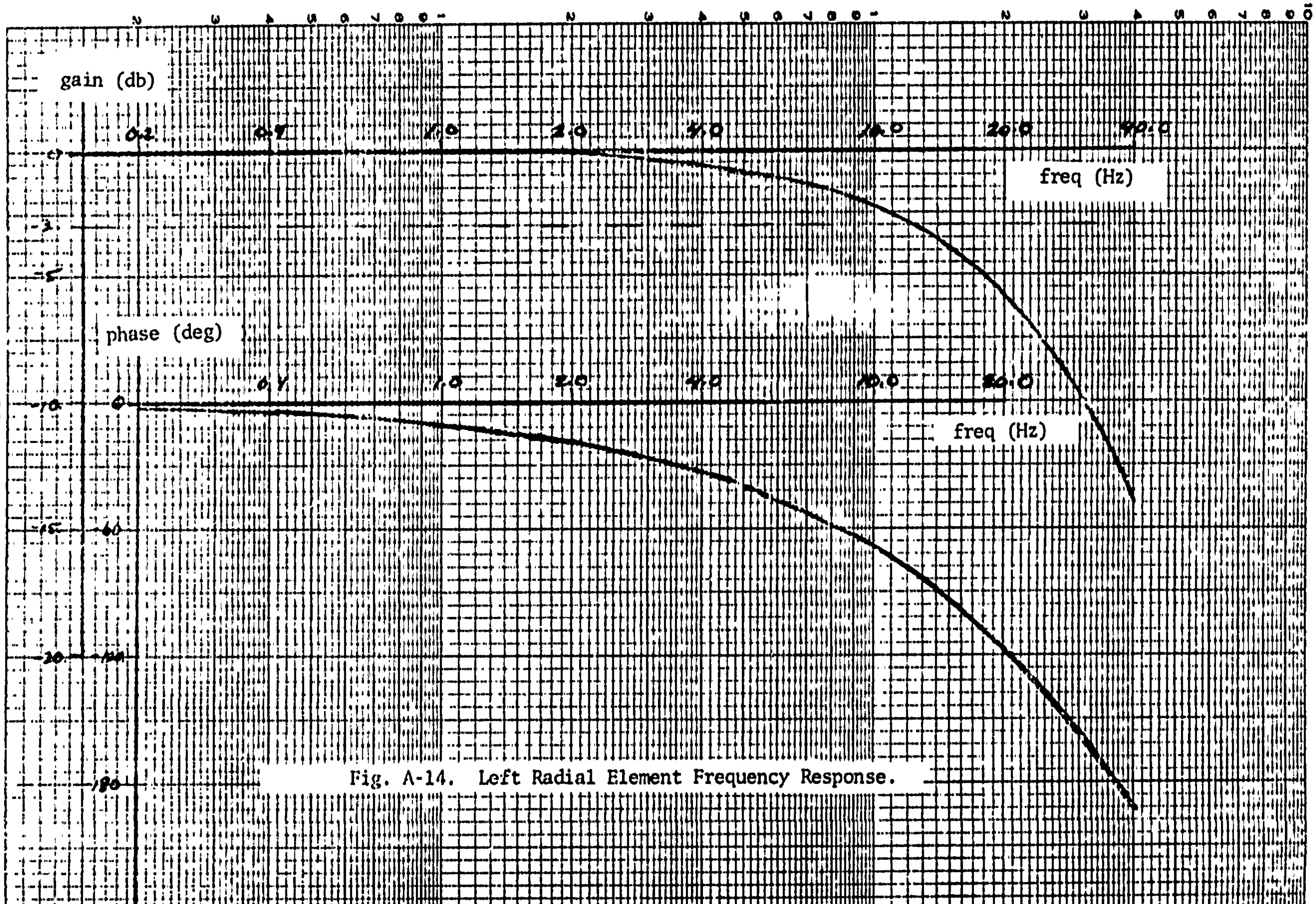

Fig. A-14. Left Radial Element Frequency Response.

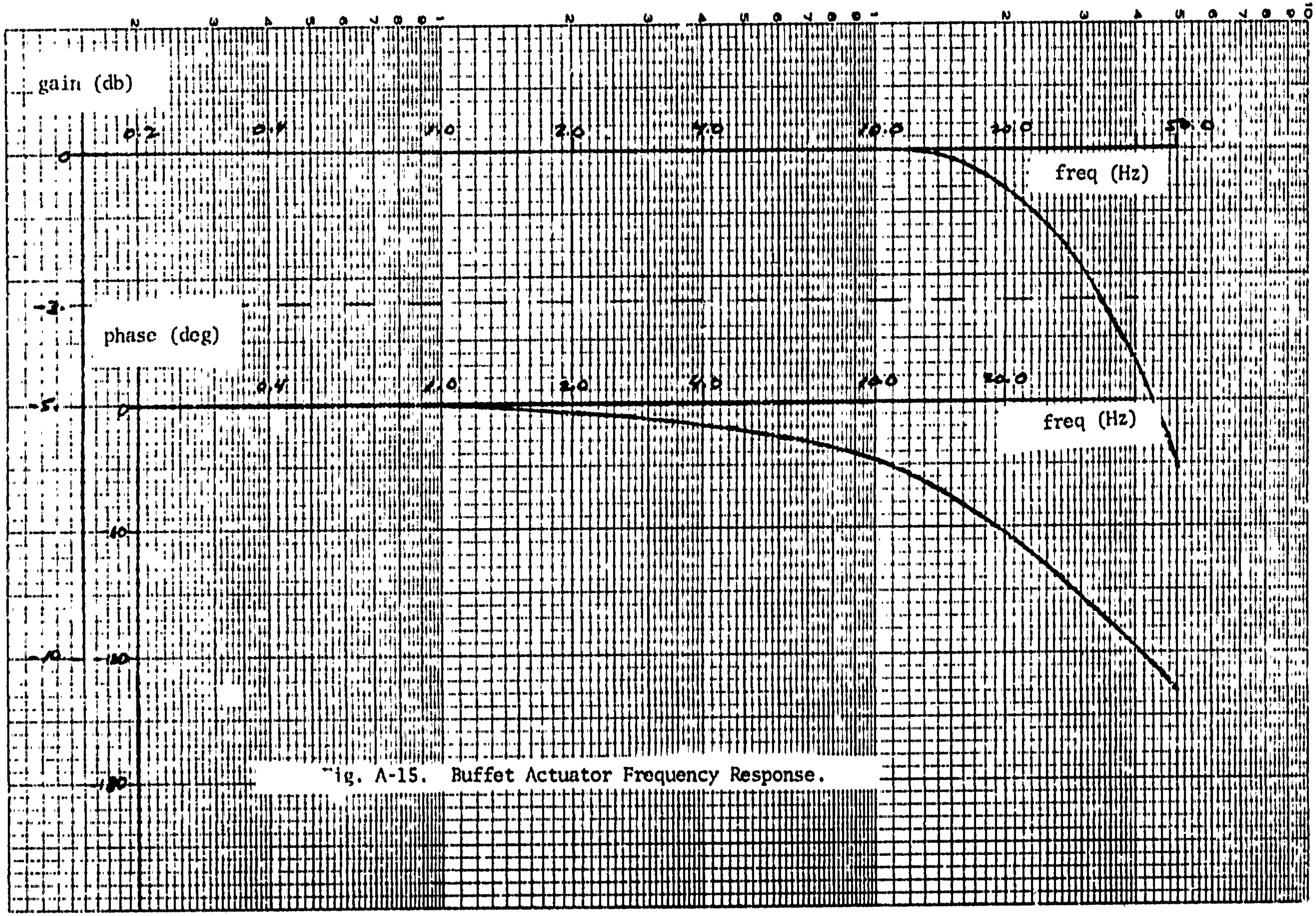

Fig. A-15. Buffet Actuator Frequency Response.

APPENDIX B: TIME RESPONSE DATA

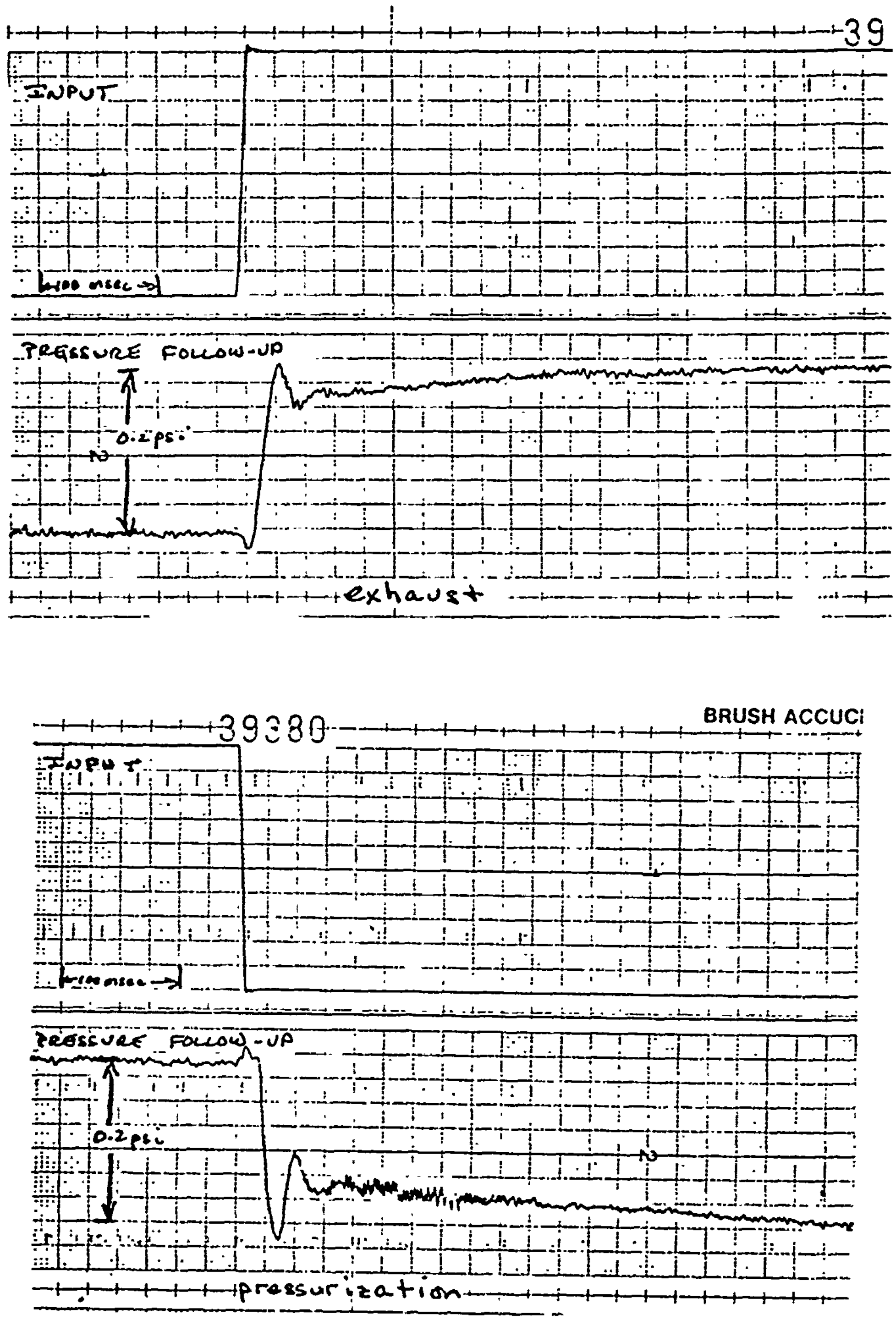

Figure B1. Backrest Bladder Step Response

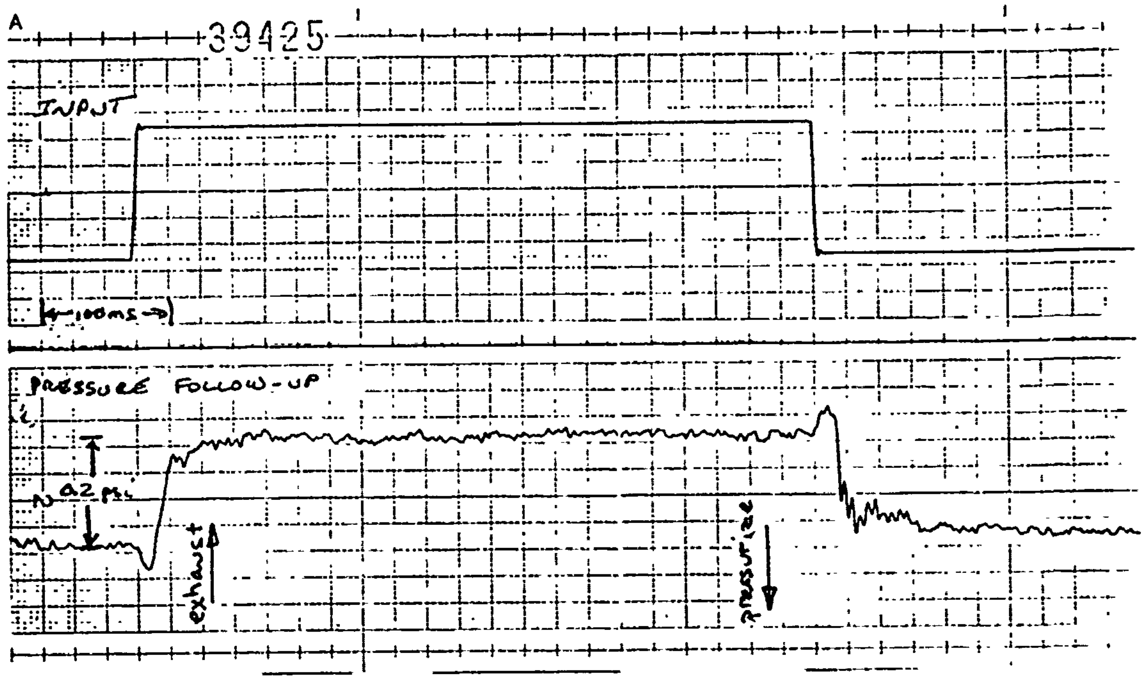

Figure B2. Left Seat Pan Bladder Step Response

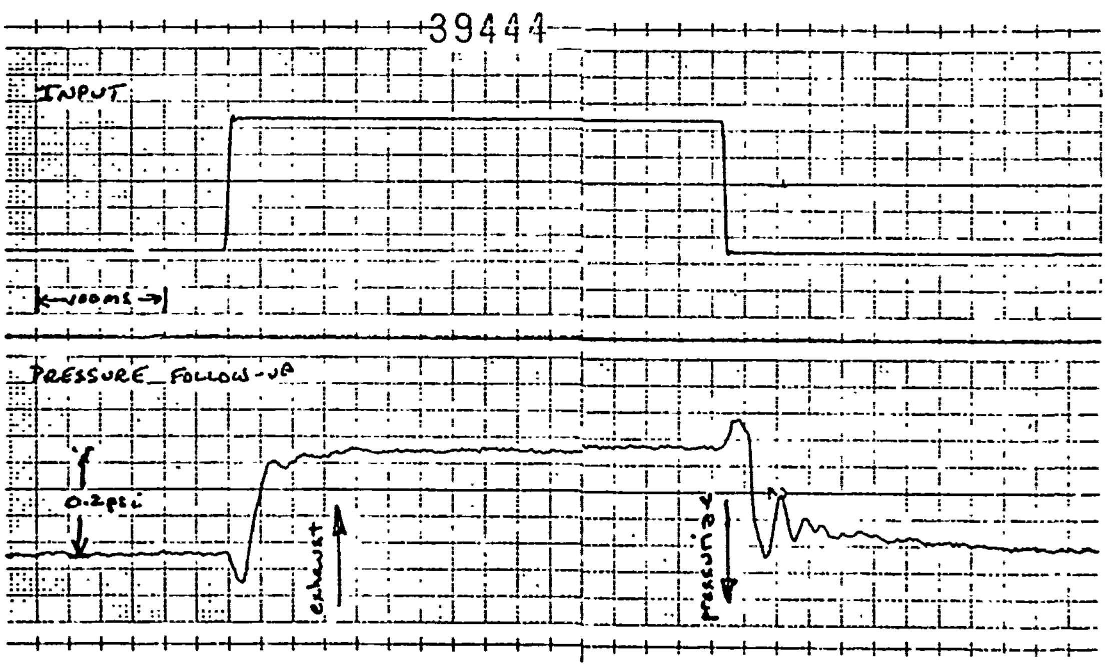

Figure B3. Right Seat Pan Bladder Step Response

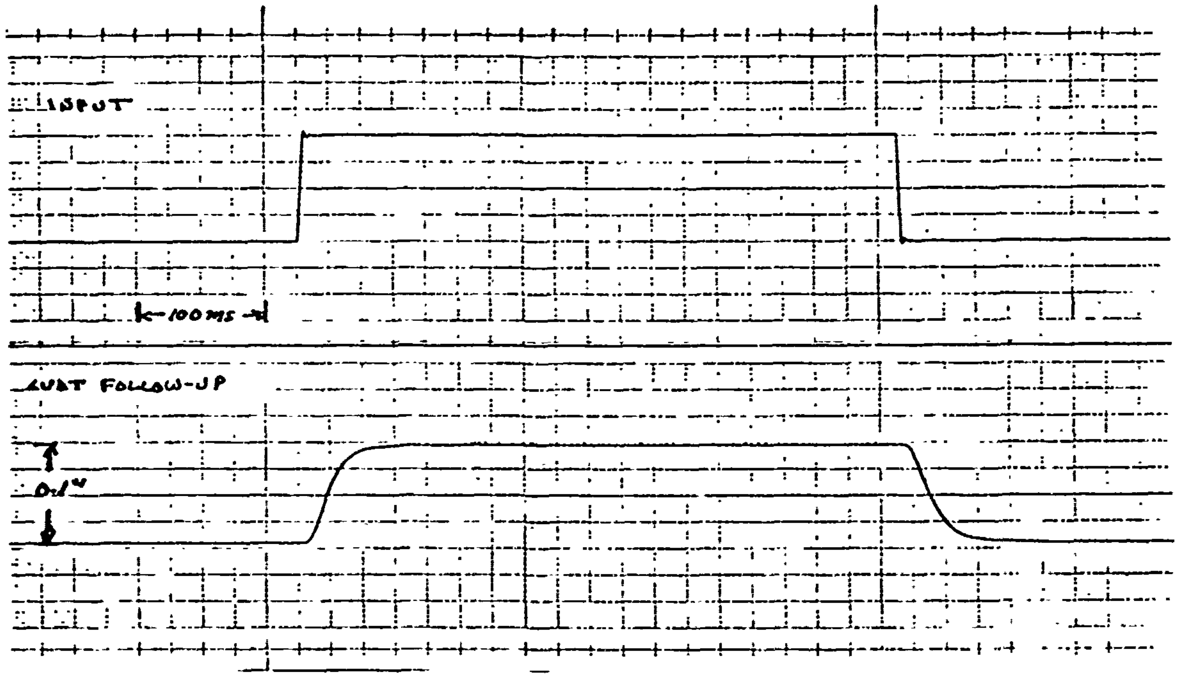

Figure B4. Front Seat Pan Actuator Step Response

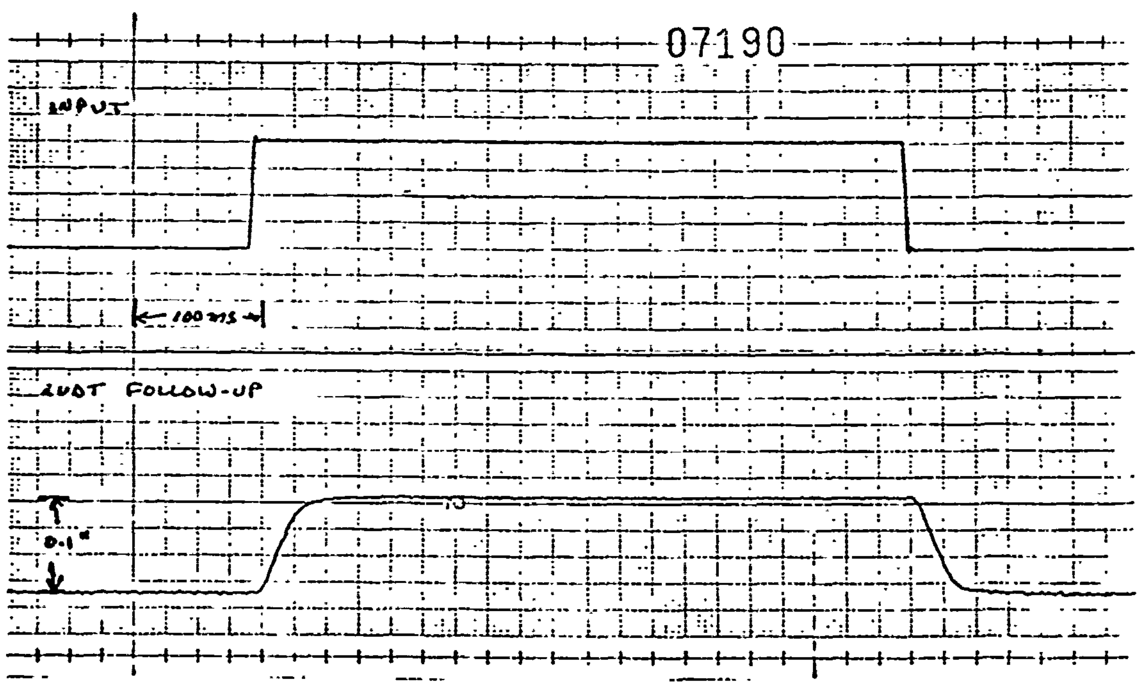

Figure B5. Right Seat Pan Actuator Step Response

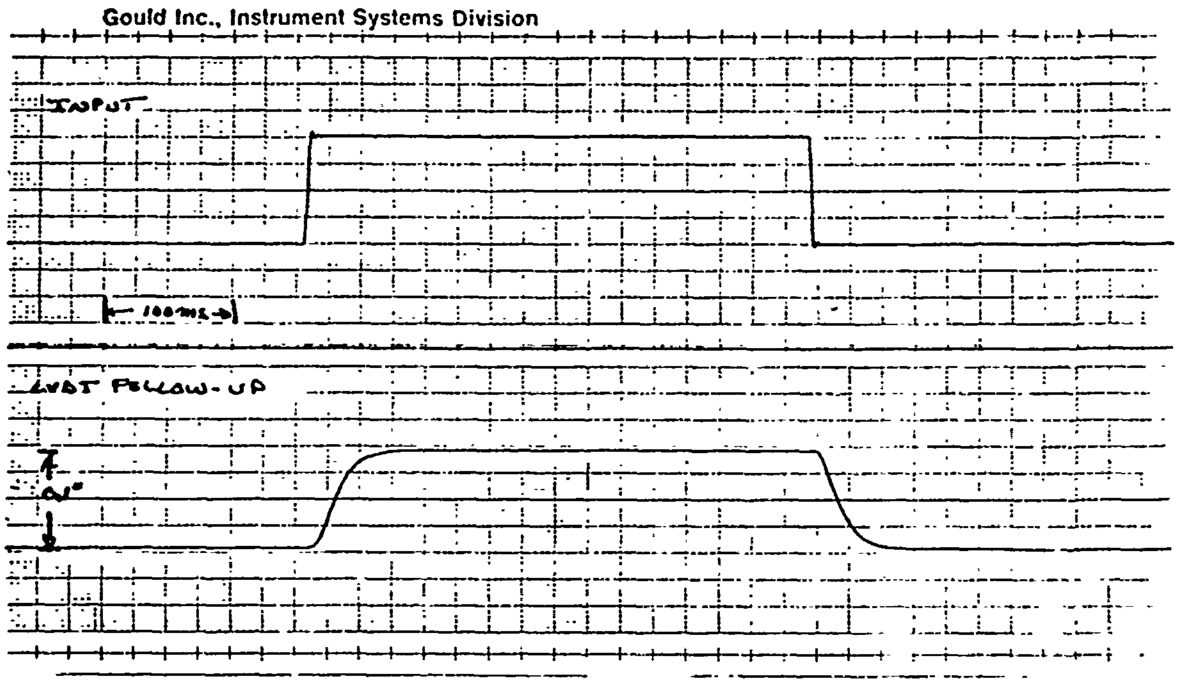

Figure B6. Left Seat Pan Actuator Step Response

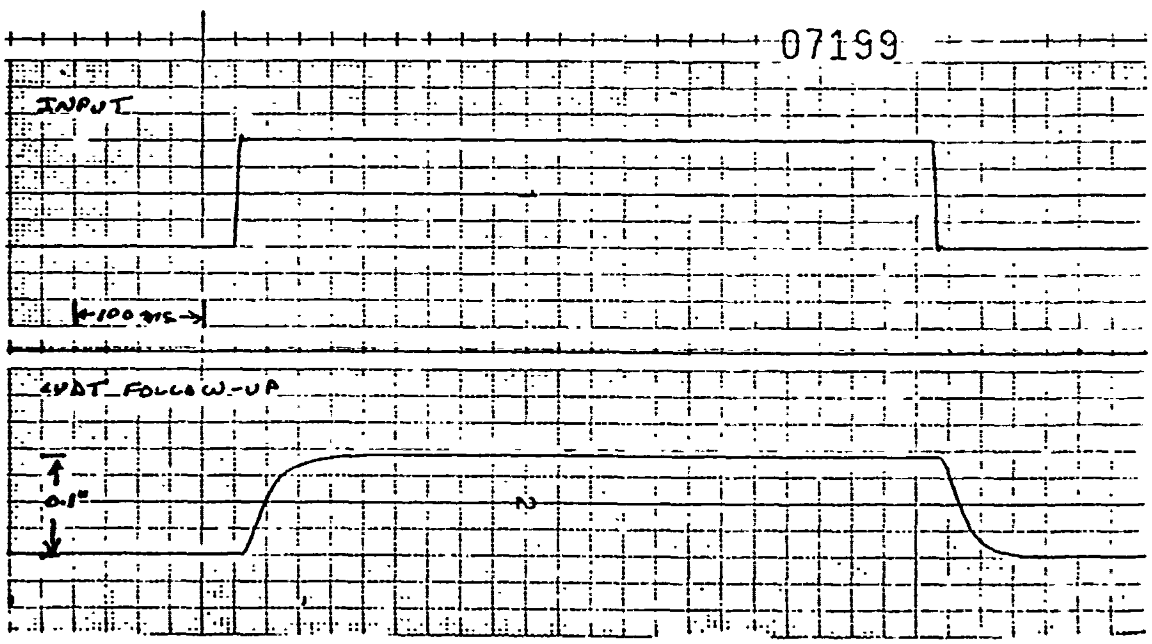

Figure B7. Longitudinal Seat Pan Actuator Step Response

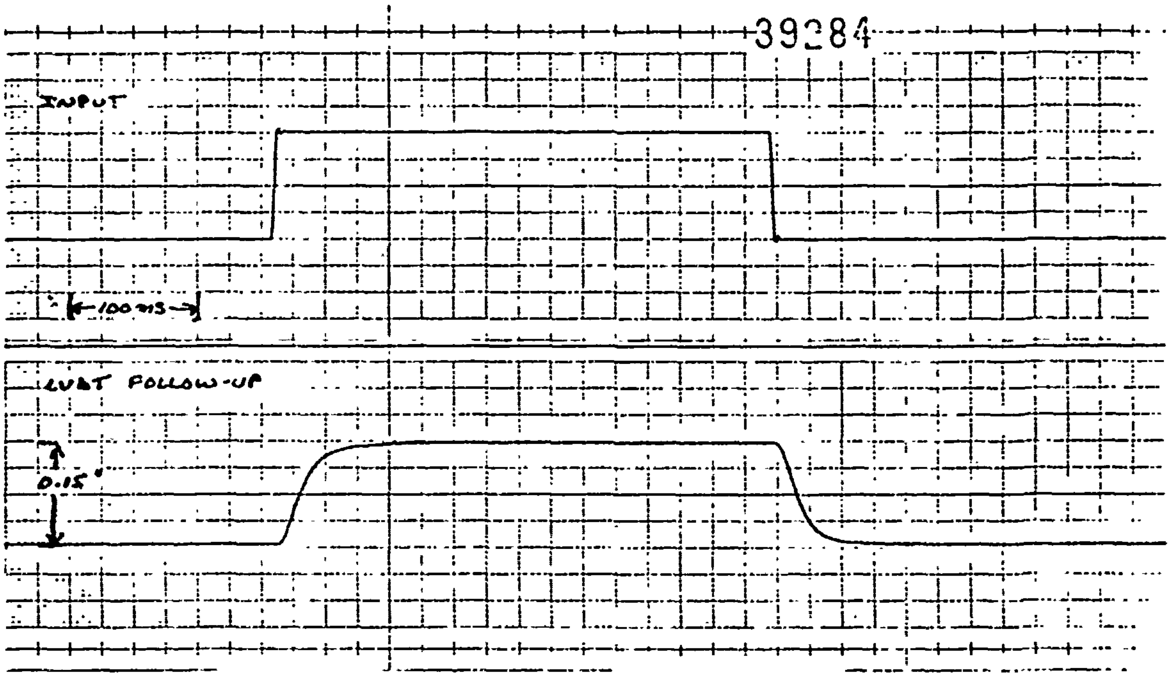

Figure B8. Right Lap Belt Actuator Step Response

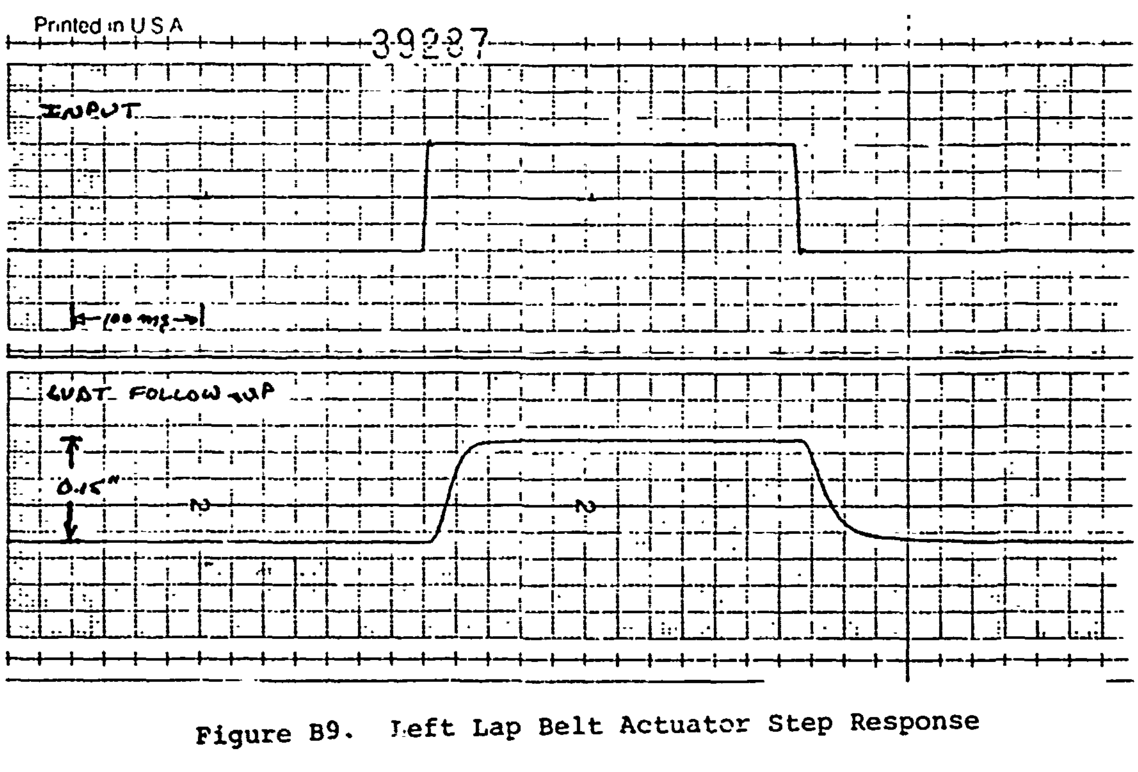

Figure B9. Left Lap Belt Actuator Step Response

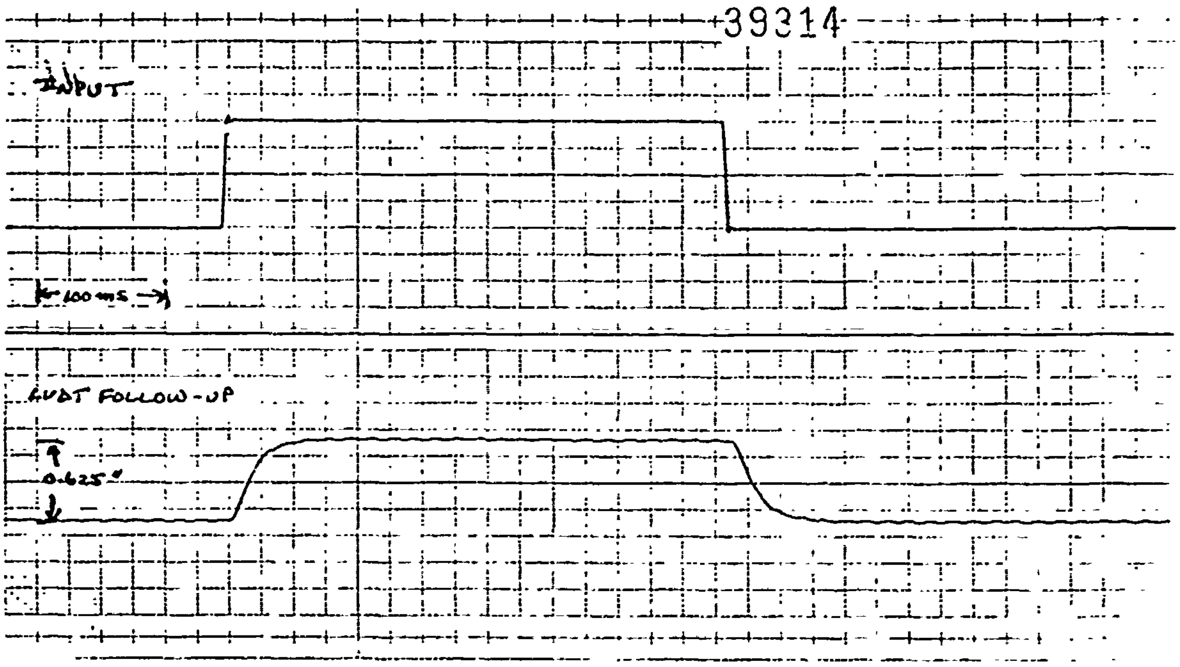

Figure B10. Top Backrest Actuator Step Response

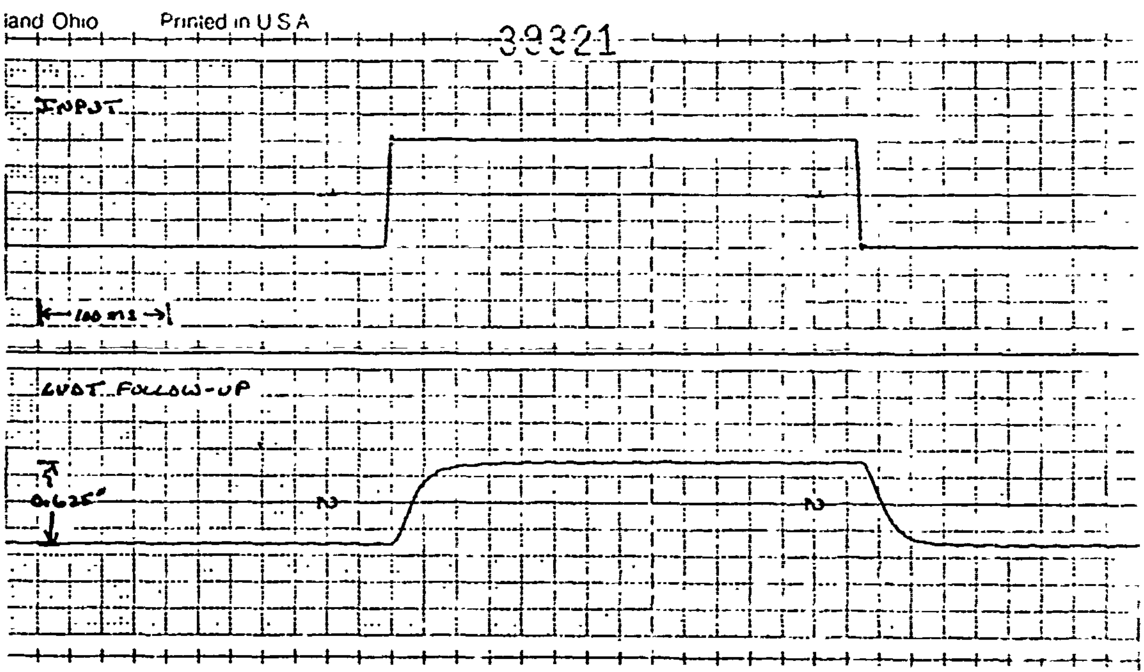

Figure B11. Right Packrest Actuator Step Response

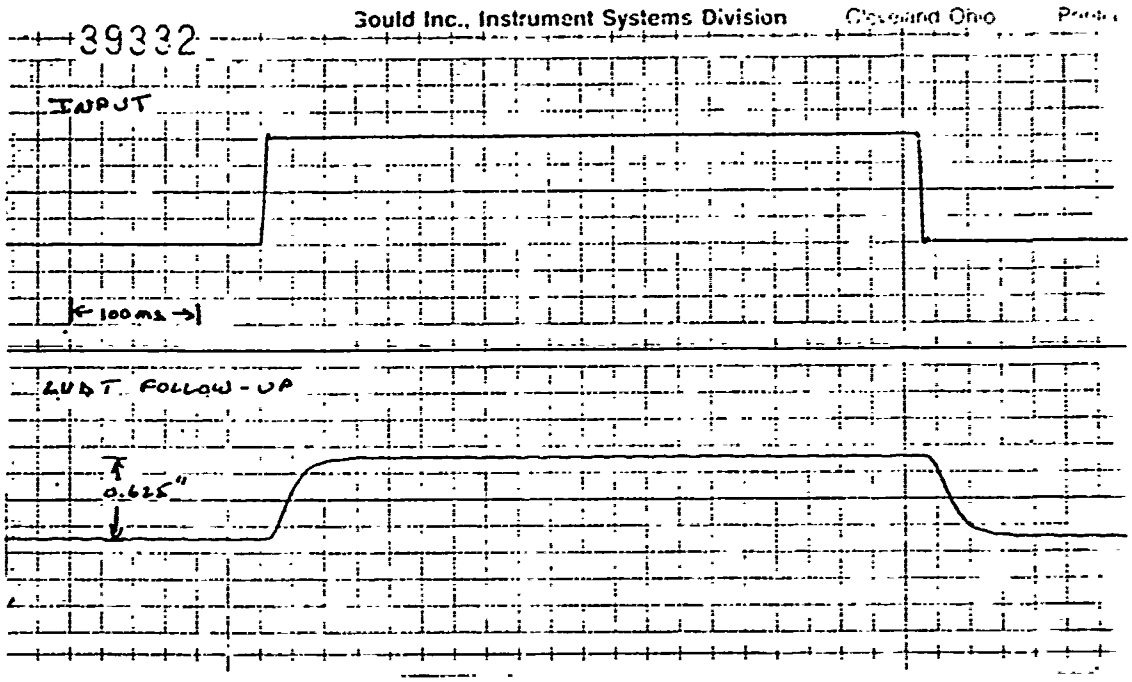

Figure B12. Left Backrest Actuator Step Response

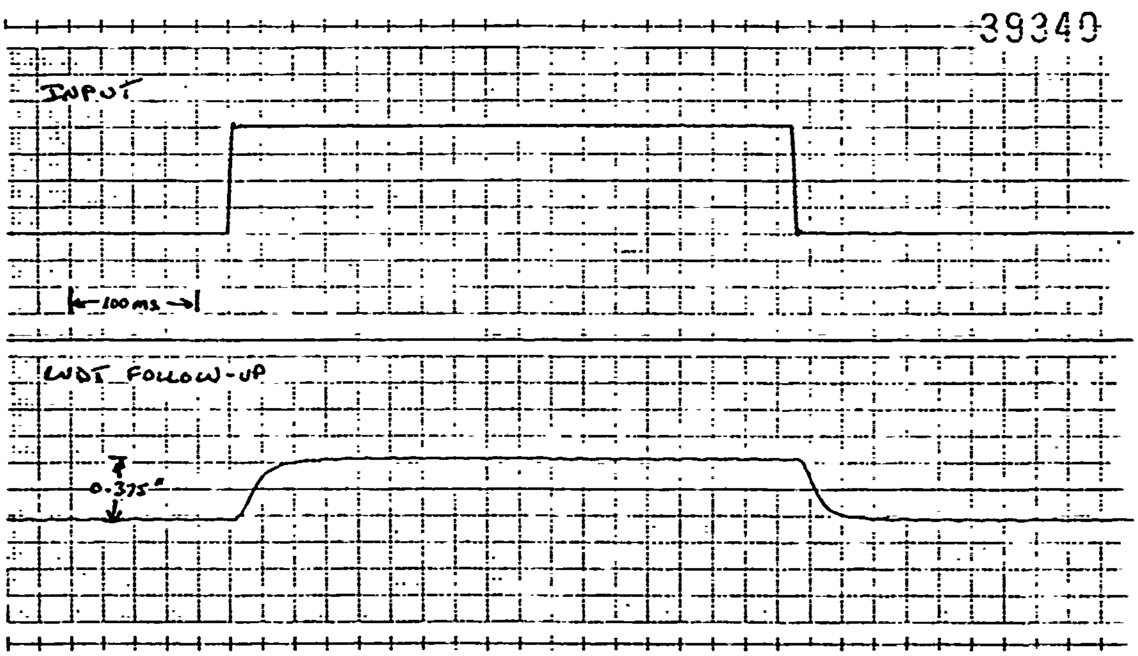

Figure B13. Right Radial Element Step Response

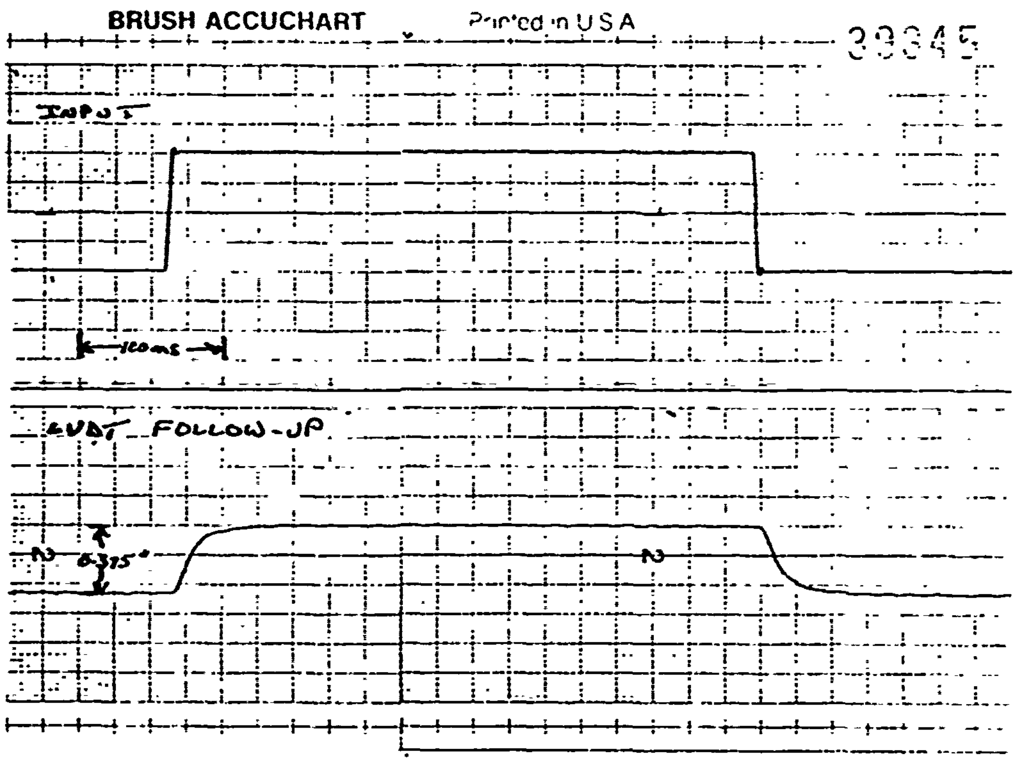

Figure B14. Left Radial Element Step Response

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